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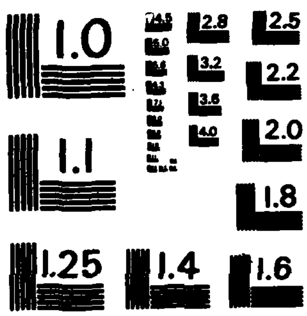

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THE SIMULATION OF A PASSIVE SOLAR ENERGY SYSTEM

THESIS

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THE SIMULATION OF A PASSIVE
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THE SIMULATION OF A PASSIVE SOLAR ENERGY SYSTEM

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by
Mitchell P. Slate
Captain USAF
Graduate Astronautical Engineering

December 1982

Preface

Interest in the use of solar energy to supplement conventional methods of heating the interior of structures has grown with the price of conventional fuels. A method of predicting the thermal performance of structures heated passively by the sun would be very useful in determining the cost effectiveness of a particular design. A computer simulation model capable of estimating the hourly performance of a residential size structure with a variety of passive solar heating features is described in this work. Many designs can be investigated by making changes in the input parameters.

I wish to thank Dr. James E. Hitchcock, my thesis advisor, for the guidance and encouragement he gave to me. Without his efforts, this document would not exist.

I would especially like to thank my wife Helen. Her untiring support and understanding during this busy time helped me more than she will ever know.

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List of Symbols

English Symbols	Quantity	Units
A_{DG}	Area of Direct Gain Collector	ft^2
A_R	Interior Surface Area	ft^2
A_{SS}	Surface Area of Mass in Sunspace	ft^2
A_{TW}	Area of Trombe Wall Collector	ft^2
Cx	Heat Capacity of Capacitor x	B/F
C_p	Specific Heat	B/lbm-F
F	Perimeter Edge Heat Loss Factor	B/ft-hr-F
$\bar{H}$	Monthly Average Daily Total Radiation on a Horizontal Surface	B/ft^2-day
$\bar{H}_d$	Monthly Average Daily Diffuse Radiation on a Horizontal Surface	B/ft^2-day
h_{SS}	Heat Transfer Coefficient from Mass Surface to Air in the Sunspace	B/ft^2-hr-F
I	Hourly Total Radiation on a Horizontal Surface	B/ft^2-hr
I_b	Hourly Beam Radiation on a Horizontal Surface	B/ft^2-hr
I_{bv}	Hourly Beam Radiation on a Vertical Surface	B/ft^2-hr
I_d	Hourly Diffuse Radiation on a Horizontal Surface	B/ft^2-hr
I_{tv}	Hourly Total Radiation on a Vertical Surface	B/ft^2-hr
$\bar{K}_T$	Monthly Average Clearness Index	-
$\dot{m}$	Mass Flow Rate	lbm/hr
n	Air Infiltration Rate	1/hr

English Symbols	Quantity	Units
P	Length of Building Perimeter	ft
Q_{AUX}	Heat Output of the Furnace	B/hr
Q_{DG}	Heat Gain due to Direct Gain Radiation	B/hr
Q_{DSM}	Heat Transferred to the Detached Storage Mass	B/hr
Q_L	Heat Generated by Appliances	B/hr
Q_{SS}	Heat Transferred from the Mass to the Air in the Sunspace	B/hr
Q_{TW}	Heat Gain at the Surface of the Trombe Wall	B/hr
R	Resistance to Heat Flow	ft^2-hr-F/B
Rx	Resistance of Resistor x	hr-F/B
R_b	Ratio of Beam Radiation on a Tilted Surface to Beam Radiation on a Horizontal Surface	-
Tx	Temperature at Node x	F
T_a	Ambient Temperature	F
T_{ave}	The Monthly Average Ambient Temperature	F
T_{DSM}	The Temperature of the Center of the Detached Storage Mass	F
T_{eu}	The Equivalent Uniform Temperature	F
T_i	The Interior Temperature	F
T_M	Surface Temperature of Thermal Mass in the Sunspace	F
T_{mr}	Mean Radiant Temperature of Interior Surfaces	F
T_r	Range of Comfortable Temperatures	F
T_{SS}	Temperature of Air in the Sunspace	F

English Symbols	Quantity	Units
T_{swing}	The Monthly Average Ambient Temperature Swing	F
V	Volume	ft^3
Greek Symbols		
α	Effective Cavity Absorptance	-
β	Collector Surface Tilt Angle	degrees
δ	Declination	degrees
γ	Collector Azimuth Angle	degrees
ρ	Density	lbm/ft^3
ρ_g	Ground Reflectance	-
ρ_R	Interior Mean Reflectance	-
τ_b	Beam Transmittance of Glass	-
τ_d	Diffuse Transmittance of Glass	-
$\tau\alpha_b$	Effective Transmittance-Absorptance Product for the Trombe Wall for Beam Radiation	-
$\tau\alpha_d$	Effective Transmittance-Absorptance Product for the Trombe Wall for Diffuse Radiation	-
ϕ	Latitude	degrees
ω	Hour Angle	degrees
ω_s	Sunset Hour Angle	degrees
θ	The Angle between Beam Radiation on a Surface and the Normal to the Surface	degrees
θ_z	The Angle Between Beam Radiation and the Normal to a Horizontal Surface	degrees

Abstract

A simple lumped capacitance-resistance model is used to simulate heat flow in a residential size structure heated passively by the sun. The model takes the form of an analogous electrical circuit. A computer program was written to analyse the circuit. By altering the input parameters of the program, the thermal performance of a wide variety of passive solar designs can be investigated for any geographical location. By comparing program generated data to data taken from experimental test cells in Los Alamos, New Mexico, it was found that the simulation program predicted energy use to within 4 percent of measured values. Also, the computer program predicted temperature swings to within 16 percent of measured swings. Correlation with empirical methods of calculating monthly and annual savings in fuel use for heating was poor. Using the simulation calculations as a base, the predictions of annual savings differed by as much as 76 percent.

THE SIMULATION OF A PASSIVE SOLAR ENERGY SYSTEM

I Introduction

Background

Only recently has interest in solar energy for space heating become widespread. From ancient civilizations, however, comes evidence of construction with the thermal effect of the sun in mind. Early Greeks, Egyptians, and Persians built structures that accepted solar radiation in the winter, yet shaded the structure's interior in the summer. In North America, the Pueblo Indians built cliff dwellings in the Southwest as early as 1000 A.D. Erected in the depressions of vertical south facing natural formations, the buildings were shaded from the summer sun by overhangs. Wintertime brought the sun to lower elevation angles, where the adobe walls were directly irradiated. These bricks held their warmth long after the sun went down. Whether the Pueblos first erected their dwellings for thermal comfort or as defense from enemies is uncertain. Nonetheless, the benefits of passive solar control were certainly recognized and exploited in later constructions.

In this century, solar energy has been largely ignored. Vast quantities of coal, oil, gas, and water power at low cost have made the added cost of passive solar construction unnecessary. Now, with utility costs rising, efficient solar designs can be more economical in the long run by

offsetting higher construction costs with lower utility bills.

Economic analysis methods exist to determine the advisability of selecting a specific solar design, given its thermal performance. Calculating thermal performance is more difficult. Around the country, climatic conditions: temperatures, precipitation, solar insolation, cloudiness, and air quality vary widely. These factors and more affect how well a solar house will perform. Procedures to calculate thermal performance began to emerge in the 1960's. The two basic types of procedures are empirical methods and simulation.

Empirical techniques, such as the popular Solar Savings Fraction (SSF) method developed by Balcomb (Ref 1), allow one to estimate the savings in monthly heating bills for a specific solar design, based on a few correlating parameters. Use of the SSF method entails balancing monthly solar heat gain against monthly heat loss from a structure, then reading from a graph the percentage that furnace use will decrease compared to a similar house without a solar collector. Calculations take only a few hours and results are accurate for long term analysis. The problem with empirical techniques is that safeguards against poor designs are minimal. For example, increasing the solar collector area may very well cut down on heating bills, but may also cause the interior to overheat on a sunny day.

To guard against hidden design defects, one must look at the temperature swing (the difference between the

maximum and minimum interior temperature) for the structure. This involves a great deal of lengthy simulation calculations (solving sets of differential equations) and is done on the computer. Several heat transfer simulation programs, such as the Transient System Simulation Program (TRNSYS), (Ref 2), and DOE2 (Ref 3) have been developed recently. These large, complex programs calculate heat flow rates for both active and passive solar heating systems. At hourly or shorter intervals, the programs will report temperatures in various building components. Using the print-out, the designer can determine not only the economy of a design, but can also insure that interior temperatures stay within acceptable limits. Such programs do have drawbacks, however. While versatile, they are large. The 1974 version of TRNSYS consists of almost 5000 FORTRAN statements. Later versions are larger. In addition, these large programs can be cumbersome to operate, especially if a variety of designs are under consideration.

Purpose

The purpose of this study was to devise an efficient transient simulation program capable of analysing a variety of passive solar designs. It should give the energy savings for a particular design and predict with reasonable accuracy the temperature swing. The program should be small enough to fit on the micro-computers that are showing up in design offices and be quick and easy to use. Combined with an economic analysis method, the solar program could be

used to pick the most economical design from several such designs.

Approach

The structure was modeled using an electrical circuit analog. Resistors and capacitors were used to simulate insulation and thermal mass, respectively. Electrical potentials corresponded to temperatures at physical locations within the structure. Differential or algebraic equations for each node in the circuit diagram were derived and these equations were solved on the computer using numerical techniques. Output gave a history of solar heat gain, nodal temperatures, and auxiliary heating requirements for a twenty four hour period on typical days for each month of the year.

The development of the transient simulation program is presented in the next two sections. Then, the program verification, performed by attempting to accurately simulate an instrumented test structure set up in Los Alamos, New Mexico, is presented. Finally, a hypothetical residential size structure located in Columbus, Ohio was modeled. The thermal performance of a conventional structure was compared to the performance of several passive solar alternatives.

II Solar Design Analysis

The details a solar engineer must consider in designing a structure that will be heated by the sun are presented in this section. First, the design concepts involved will be discussed. Next, heat flow in a structure will be examined. Thermal energy for the building comes from the sun, from internal equipment and people, and from a furnace. Heat is lost through the ceiling, walls, and floor. Infiltration of outside air in and inside air out also contributes to heat loss. After detailing the heat flow, the Life Cycle Savings Method of economic analysis will be described. Finally, a few human factors will be considered. In order to design a comfortable house, one must establish a definition for "comfortable."

Solar House Designs

Basically two categories of solar heating systems exist. An active system involves the use of pumps and or fans to move a working fluid, air or water, from the solar energy collector, usually mounted on the roof, to a separate storage mass for heat retention or directly to the living area. Without some form of energy, such as electricity, to run the pumps or fans, an active solar energy system will not work. A passive solar heating system requires no auxiliary energy source. The structure itself is designed to collect and store solar energy. The walls and floor can do double duty, supporting the roof and storing heat. Large windows not only allow one

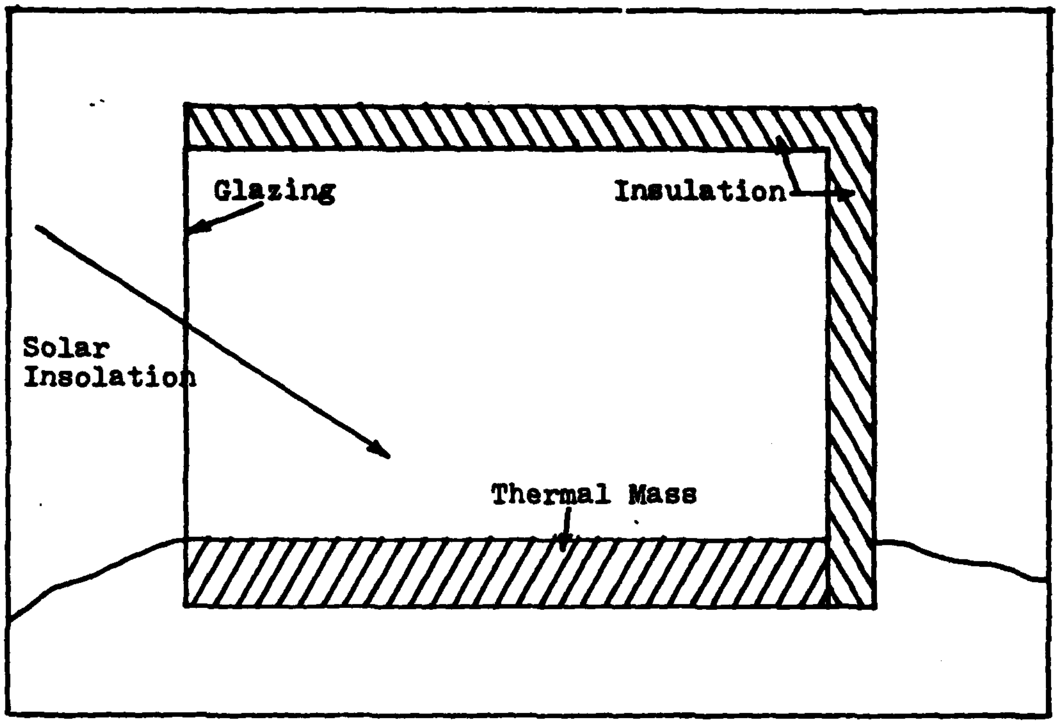

Fig. 1 Structure with Direct Gain Solar Heating

to see out, but admit solar radiation. All heat flow in the passive solar structure is by radiation, conduction, and natural convection. Passive system designs can be further broken down. One can consider direct gain or indirect gain configurations.

The simplest passive solar heating concept is direct gain heating, as shown in Fig 1. The sun shines through south facing glazing; provided the structure is located in the Northern Hemisphere; straight into the living area. The floors, walls, and furniture heat up as a result of this direct insolation. The interior and occupants are warmed by convection and radiation from the heated surfaces.

The living area acts as solar collector, storage mass, and heat distribution system.

The advantages of a direct gain system are its simplicity, low cost, and large window area. As shown in Fig 1, the system consists of windows and thermal mass. These are easy and relatively inexpensive to build. In addition, the windows allow pleasing visual access to the outside.

Direct gain systems also have disadvantages. The large expanse of glass can allow the interior to become too bright on a sunny day. Also, ultraviolet radiation bleaches many fabrics. Unless a sizeable amount of heat absorbing mass is present, the living area will heat up quickly during daylight hours, possibly overheating. Then, during the night, the building will lose heat through the glazing by convection and radiation from the building interior to the inner surface of the glazing, conduction through the glazing, and convection and radiation from the exterior surface.

The second passive heating design is indirect gain. Here, heat is collected and transferred first to the thermal storage mass. Then, the heat is conducted through the mass and convected and radiated to the interior. The most common indirect gain system is the Trombe wall. It consists of a double glazed masonry wall that has the glazed side exposed to the sun and the other side facing the interior of the structure. See Fig 2. Sunlight warms the outside surface of the wall and the air in the space between the glazing and the wall. Heated air from the air space can be circulated through vents to the interior to obtain immediate

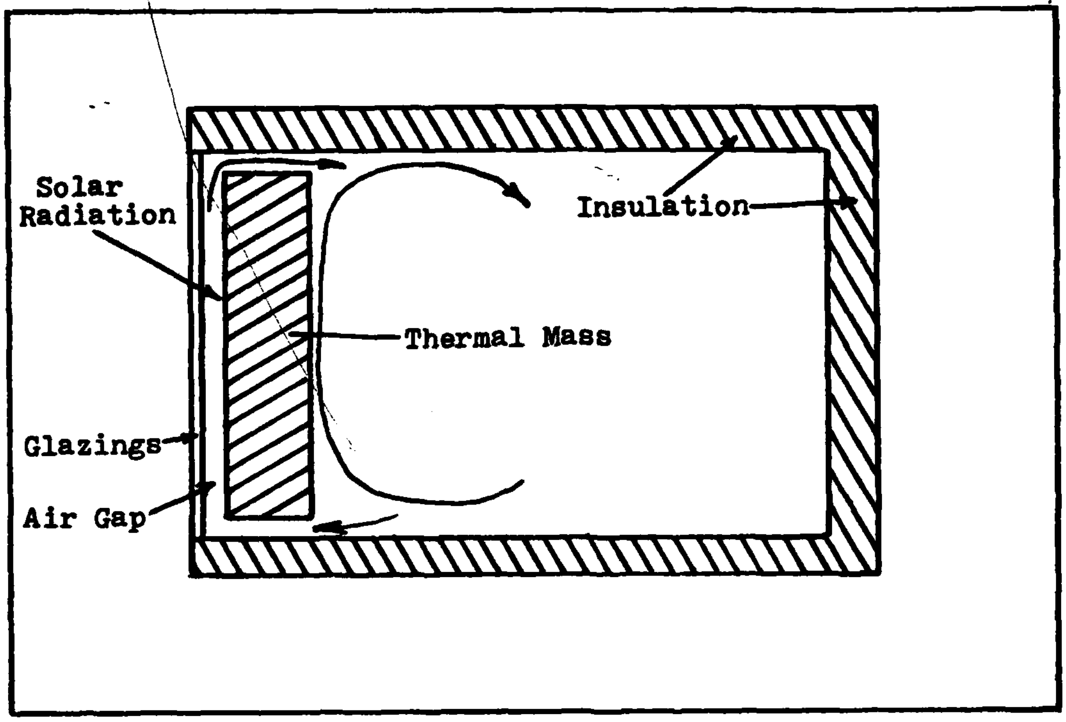

Fig. 2 Structure with a Trombe Wall

energy gains, while heat conducted through the wall enters the interior some hours later.

The Trombe wall has advantages over a direct gain system. First, glare and bleaching are not a problem. Next, the interior is not subject to a large temperature swing. Because objects inside the living area are not directly irradiated, there is less chance of overheating during the day. Also, because the interior is not exposed to a large expanse of glass, heat losses are held down at night. In fact, a Trombe wall will continue to heat room air long after the sun has gone down. For a twelve inch thick masonry wall, the delay from the time the sun heats the outside of the wall until the time when this heat soaks through

to the interior can be eight hours or more. If the sun sets at 4:00 p.m., this Trombe wall will continue to heat the interior until midnight.

The chief disadvantage of the Trombe wall is its heat loss. The most efficient way of heating the contents of the interior during the day is by directly irradiating them with sunlight. By irradiating the outside surface of a wall, some heat soaks into the wall, but loss does occur through the glazing to the outside in the same fashion as through direct gain glazing. This loss continues at night as well.

If the storage mass could be insulated from the outside, more heat would find its way to the interior, and less would be lost to the outside. One way to accomplish this is to detach the storage mass from the collector and place it at the back of or below the structure. Heated air from the collector would be transferred by natural convection or by fan to the detached storage mass, through the mass, and back to the sunspace. See Fig 3. Because the mass is well insulated from the outside, more heat will be available for the interior. In addition, the south side of the living space would be insulated conventionally, further reducing heat loss.

When designing a passive solar structure, a mix of direct and indirect features might be incorporated. The designer would try to maximize the average temperature gain over outside temperature, keep the temperature swing within acceptable limits, and minimize the amount of costly thermal

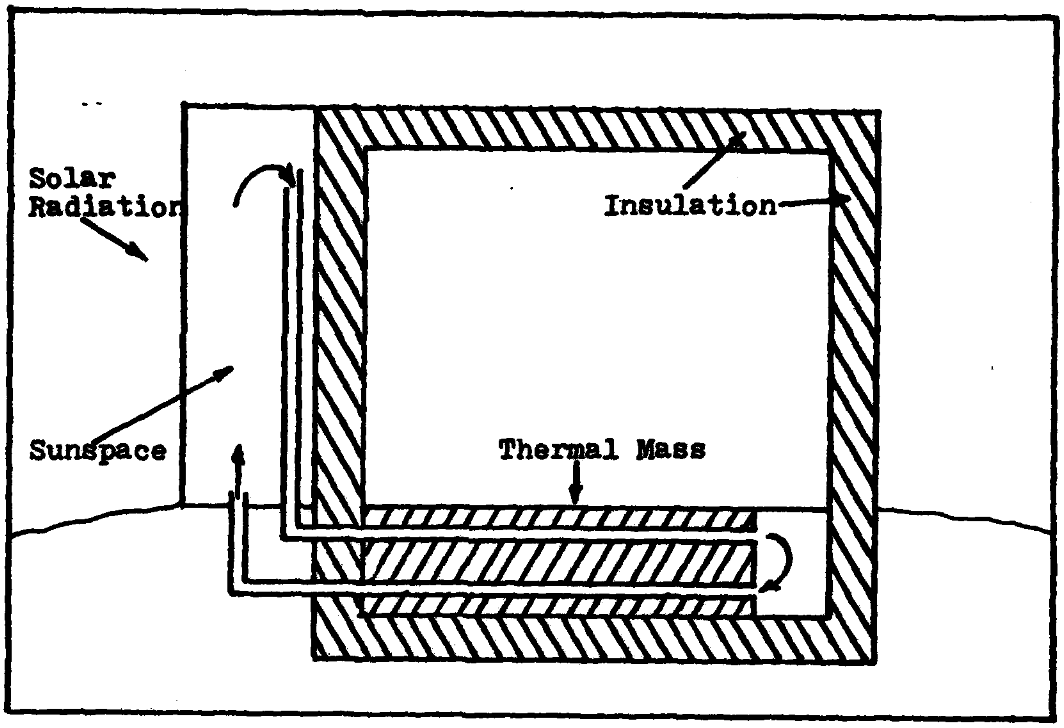

Fig. 3 Structure with Detached Storage Mass

mass that needs to be installed.

Heat Gain in the Structure

The interior of a structure is heated by the sun directly and indirectly, by internal equipment such as ovens and water heaters, by people, and by a furnace. Each of these mechanisms for heat gain will be discussed.

Solar Energy. Just outside Earth's atmosphere, the energy incident on a flat surface directly facing the sun would be 1362 W/m^2 (432 B/ft^2). As sunlight enters the atmosphere, the rays are subjected to the effects of the atmosphere. Some rays are reflected back by clouds into space, some rays are scattered or absorbed by particles or

air molecules, and others are transmitted to the ground where they are absorbed or reflected. The result of these atmospheric processes is that an object on the ground will receive radiation from the sun in three different forms.

The first form of radiation is beam radiation. By definition, this is radiation where the light rays are very nearly parallel. Beam radiation comes directly from the sun in a nearly straight line (bent only a slight amount by refraction) to the object in question. To receive the greatest benefit from beam radiation, the surface of a flat collector should be normal to a line drawn between the collector and the sun.

The second kind of solar radiation incident upon an object is diffuse radiation from the sky. Dust, water vapor, pollution, clouds, and the air itself tends to scatter light. The result is that light reaches an object on the surface from all directions in the sky. The best orientation for a flat collector to receive diffuse sky radiation is face up, so as to be able to view all of the sky.

The last type of solar radiation is ground radiation. Beam and diffuse sky radiation reach other objects and the ground just as it reaches the collector. Some of this radiation reflects off these surfaces toward the collector. Objects such as glass, water, and ice can reflect specularly. This means that beam radiation is reflected as beam radiation. Objects made out of concrete, grass, and earth reflect diffusely, which means that incident light is

scattered in all directions. Ground radiation can therefore be either beam or diffuse in nature. However, for a structure made out of wood, brick, and asphalt, surrounded by grass, snow, trees, and other structures, virtually all ground radiation will be diffuse.

The amount of beam, diffuse, and ground radiation that a collector receives is dependent on many factors, some of which were mentioned earlier. Collector orientation is important. A collector facing straight up will receive no ground radiation. A collector looking straight north will receive little beam radiation, for, in the Northern Hemisphere, the sun is rarely found north of an east-west meridian. Another factor that affects insolation is the sky condition. If the sun is obscured by clouds, no beam radiation will reach the collector. Also, the ratio of diffuse to beam radiation will be greater in New Orleans on a humid day than in Albuquerque on a dry day. Other factors that affect the kind and amount of radiation reaching a collector include time of day, building overhangs, adjacent trees or structures blocking morning or evening sunlight, the location of the collector, and the time of year.

Over the years, solar radiation data collection stations have been set up around the world. Information on hourly, daily, monthly, and annual total radiation; clearness indicies; and temperatures are available in tabular form. Perhaps the most readily available data is monthly-

average daily total radiation on a horizontal surface, monthly-average clearness index, and monthly-average temperature.

To be useful for simulations, solar insolation values for any time during the day must be available. Duffie and Beckman (Ref 4) devised an algorithm for converting monthly-average daily total radiation into beam and diffuse components of hourly radiation. Before outlining the technique, a few terms need to be defined.

The hour angle ω is the angular displacement of the sun east or west of the local meridian due to the rotation of the earth on its axis, i.e., 15 degrees per hour. The hour angle corresponding to solar noon is zero. Morning hour angles are negative. The hour angle is given in degrees by

$$\omega = 15\ (\text{TIME OF DAY}) - 180$$

where, for example, 1330 hours would be 13.5.

The declination δ is the angular position of the sun at solar noon with respect to the plane of the equator. Because the earth's axis is tilted 23.45 degrees to the normal to the plane of the ecliptic, the declination will, depending on the day of the year, be at, or within limits of $\pm$ 23.45 degrees.

$$\delta = 23.45 \sin(360(284 + (\text{DAY OF YEAR})) / 365)$$

The solar collector can be located at latitude ϕ, and be oriented as to azimuth γ, and tilt β. If a collector is facing south, it has an azimuth of zero. If it is facing

east of south, its azimuth is negative. If a collector is horizontal, its tilt is zero. If it is vertical, the tilt is 90 degrees.

The sunset hour angle is the hour angle at which the sun sets.

$$\omega_s = \arccos(-\tan\phi \tan\delta)$$

Given the monthly-average daily total radiation $\bar{H}$ and the monthly-average clearness index $\bar{K}_T$, the monthly-average daily diffuse radiation $\bar{H}_d$ is calculated with the following relation:

$$\bar{H}_d = \bar{H}\,(0.775 + 0.00653\,(\omega_s - 90) - (0.505 + 0.00455\,(\omega_s - 90))\cos(115\,\bar{K}_T - 103)) \qquad (1)$$

The hourly total radiation I is

$$I = \bar{H}\,((\pi/24)\,(a + b\cos\omega)\,(\cos\omega - \cos\omega_s) / (\sin\omega_s - (2\pi\omega_s/360)\cos\omega_s)) \qquad (2)$$

where

$$a = 0.409 + 0.5016\sin(\omega_s - 60)$$

and

$$b = 0.6609 - 0.4767\sin(\omega_s - 60)$$

The hourly diffuse radiation I_d is

$$I_d = \bar{H}_d\,((\pi/24)\,(\cos\omega - \cos\omega_s) / (\sin\omega_s - (2\pi\omega_s/360)\cos\omega_s)) \qquad (3)$$

Then, hourly beam radiation is the hourly total less the hourly diffuse radiation.

$$I_b = I - I_d \tag{4}$$

The values of hourly beam and diffuse radiation calculated with the above relations are for a collector that is facing straight up. The collector for a residential size structure passively heated by the sun will, in the vast majority of the cases, be a glass window hung vertically, facing generally south. The values for hourly beam and diffuse radiation must be altered for a collector that has this orientation.

Hourly beam radiation I_b must be multiplied by a geometric factor R_b which is the ratio of beam radiation on a tilted surface to that on a horizontal surface.

$$R_b = \cos\theta \,/\, \cos\theta_z \tag{5}$$

where the angle of incidence θ is the angle between the direction of beam radiation and the normal to the collector surface. The zenith angle θ_z is the angle between the direction of beam radiation and the normal to a horizontal surface. The angle of incidence and the zenith angle can be calculated from the following relations:

$$\cos\theta = \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma + \cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega$$

$$\cos \theta_z = \sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega \tag{6}$$

For a collector oriented vertically, the tilt β will be 90 degrees. The equation for the angle of incidence is simplified to

$$\cos \theta = -\sin \delta \cos \phi \cos \gamma + \cos \delta \sin \phi \cos \gamma \cos \omega + \cos \delta \sin \gamma \sin \omega \tag{7}$$

Diffuse radiation has no preferred direction. Its intensity is the same no matter which way the collector is oriented. To maximize the collection of diffuse radiation, the collector should be exposed to as much of the sky as possible. For a window in the wall of a house, only half the sky can be sen. Overhangs, trees, and adjacent buildings will cut out additional portions of the sky. For this study, it will be assumed that one half of the sky can be seen by the collector surface. Therefore, half of the hourly diffuse radiation $1/2\ I_d$ is incident on the collector.

Additional radiation is incident on the vertically oriented collector. The amount of hourly ground radiation incident on a flat surface facing straight down is the product of the hourly total radiation I and the reflectivity of the ground ρ_g. Again, as the collector is vertical, and the ground radiation is diffuse, only half of the ground radiation available will be incident on the collector surface. This relation is given by $1/2\ \rho_g\ I$.

Given the solar radiation incident on the collector surface, the rate of heat gain for the structure can be calculated. For a direct gain system, the rate of solar gain Q_{DG} across a collector of area A_{DG} can be written as

$$Q_{DG} = A_{DG}\, \alpha\, (I_b R_b \tau_b + 1/2\, I_d \tau_d + 1/2\, \rho_g I \tau_d) \quad (8)$$

where α is the effective absorptance of the window-room combination, and τ_b and τ_d are the beam and diffuse transmittances of the window glazing, respectively. The combination absorptance α can be approximated by

$$\alpha = 1 - \frac{\tau_d \rho_R A_{DG} / A_R}{1 - \rho_R (1 - (A_{DG} / A_R) \tau_d)}$$

where ρ_R is the reflectance of the interior walls, floor and ceiling, and A_R is the area of the interior walls, floor and ceiling.

The heat collected each hour at the outer surface of a Trombe wall of area A_{TW} can be expressed as

$$Q_{TW} = A_{TW} (I_b R_b \tau\alpha_b + 1/2\, I_d \tau\alpha_d + 1/2\, \rho_g I \tau\alpha_d) \quad (9)$$

where $\tau\alpha_b$ and $\tau\alpha_d$ are the effective beam and diffuse transmittance through the glazing and absorptance of the masonry wall, respectively. This heat warms the air in the space between the glazing and the wall, and conducts into the wall itself where it is stored. While the air from the space may be circulated through vents into the interior to affect immediate interior temperature gains, this option will be omitted in this analysis for two reasons. First,

heat that is immediately circulated cannot be stored. This reduces the effectiveness of the delayed action heating that makes the Trombe wall so popular. Second, a combination of direct gain heating for early morning gains and indirect gain for later heating makes the option unnecessary.

For a detached storage mass, one must calculate the heating of the air in the sunspace and the transport of heat to the storage mass. Heat gain by any masonry in the sunspace can be calculated using Eq 9, substituting the surface area of the mass in the sunspace A_{SS} exposed to the sky for the surface area of the Trombe wall A_{TW}. This mass will heat the air in the sunspace by convection.

$$Q_{SS} = h_{SS} A_{SS} (T_M - T_{SS}) \tag{10}$$

where Q_{SS} is the rate of heat transfer from the mass in the sunspace to the air, h_{SS} is the convection coefficient, T_M is the surface temperature of the mass in the sunspace, and T_{SS} is the temperature of the air in the sunspace. Heated air from the collector is transported to the storage mass by natural or forced convection, then returned to the sunspace for further heating. The rate of energy transport to the detached storage mass is $\dot{m}\ C_p\ T_{SS}$, where $\dot{m}$ is the mass flow rate and C_p is the specific heat of air. The mass flow rate is, if by natural convection, dependent on the geometry of the system and the temperature gradients. Mass flow rates for forced convection depend on the size of the fans and resistance to flow in the ductwork. If the flow is forced, the sunspace air could be pushed through an efficient

heat exchanger until it reaches thermal equilibrium with the center of the storage mass. If this is the case, the rate at which heat is transferred to the mass is

$$Q_{DSM} = \dot{m}\, C_p\, (T_{SS} - T_{DSM}) \tag{11}$$

where Q_{DSM} is the heat flow rate and T_{DSM} is the temperature of the center of the storage mass.

Heat Gain from Non-Solar Sources. The heat generated by appliances and people within a structure is not insignificant. Schools, shopping centers, and office buildings often times have overheating problems with freezing temperatures outside. As an example, an average human body lying down will generate 300 B/hr. This heat reduces the additional energy that must be supplied by the furnace or the solar heating system.

A residential structure, with few people and little equipment, has a small amount of internal heat generated. According to the ASHRAE Handbook (Ref 5), the internal sources in a residential structure are good for a 7 degree Fahrenheit increase in the interior temperature. Accepted practice in the industry is to disregard all internally generated heat and design the heating system to maintain an interior temperature of 65 F.

The furnace in a residential structure is, most often, an on-off heat generator that heats the interior air at a constant rate when on. The furnace is controlled by a thermostat, which turns the furnace on when the interior temperature reaches a lower limit and turns it off when an

upper temperature limit is reached. In this study, the lower limit will be set at 65 F, the upper limit at 69 F.

Heat Loss From the Structure

During the winter months, valuable heat from the interior of a structure finds its way to the outside and is lost. Heat is lost by conduction through the walls, ceiling, and roof, then convection and radiation to the outside air. Heat is also lost by conduction through the ground. Lastly, heat is lost by infiltration of outside air in and inside air out. Each of these losses will be examined.

Loss through Walls, Windows, and Ceiling. This loss is calculated using the relation $Q = \Delta T / R$, where Q is the rate of heat loss, ΔT is the difference between interior and outside temperature, and R is the total thermal resistance. The resistance is calculated by summing the thermal resistances of the components of the wall, ceiling, or window.

Heat loss through the foundation is a different matter. The ground is a good insulator. Little heat is lost straight down. Most of the floor loss is around the perimeter, where the distance to the outside air is at its shortest. Most new houses built in cold climates have perimeter insulation. The resistance to heat loss in the perimeter is a function of its length, the thickness of the insulation, and the depth below ground level to which the insulation extends. For english units, perimeter resistance is given by

$$R = \frac{1}{P\ F} \qquad (12)$$

Table I Edge Loss Factor F for a Masonry Slab Floor

Insulation R-Value	Depth of Insulation		
	1 ft	1.5 ft	2 ft
10.0	0.20	0.18	0.17
6.7	0.32	0.28	0.27
5.0	0.43	0.39	0.37
4.0	0.57	0.50	0.48
3.3	0.70	0.62	0.59
2.5	1.00	0.88	0.83

From: Mazria (Ref 6)

where P is the length of the perimeter and F is an edge loss factor from Table I.

Perhaps the largest single factor contributing to heat loss is infiltration. Outside air seeps in, and inside air out through cracks around doors and windows, through stove and dryer vents and furnace flues, and through the building materials themselves. In addition, every time a door or window is opened, additional air is exchanged. For a building with no weather stripping or storm windows, the infiltration rate can be as high as four complete air changes per hour. By weatherstripping and sealing all cracks, this rate can be brought down to about 3/4 change per hour. Even at this rate, though, infiltration can account for 40 percent of the total building heating load. Further reductions would necessitate installing vapor seals, either paint or plastic sheeting on

the walls and ceiling. However, fresh air is important to the well-being of the occupants. Below one half an air change each hour, carbon dioxide, water vapor, and cooking odors build up. The resistance to heat loss is given by the relation

$$R = \frac{1}{C_p \rho V n} \qquad (13)$$

where C_p is the specific heat of air, ρ is the density of air, V is the volume of the structure, and n is the exchange rate.

Heat Capacitance in the Structure. The materials that go into a building, wood, bricks, concrete, all have a capacity to store heat. This thermal mass heats up and cools off more slowly than air surrounding the mass. A large amount of mass will moderate the temperature swing inside the structure. Calculating the heat capacity involves finding the product of the mass of each building component and its specific heat. For example, a 20 ft by 8 ft by 1 ft thick brick wall weighing 19200 pounds and having a specific heat of 0.2 B/lb_m-F will have a heat capacity of 3840 B/F. This means that for the wall to change one degree in temperature, it must gain or lose 3840 B from or to its surroundings.

Economics

Despite the advantages that solar heating has, i.e., self-sufficiency and thermal comfort, very few solar homes would be built if it were not economical to do so. The

major disadvantage of building a solar structure is its high initial cost. Passive solar structures require a great deal of glazing with its necessary framing, and heavy walls and floors. While frames and walls can be incorporated into the support structure of the building, the construction cost for a solar dwelling is higher than that for a conventional one. On the other hand, a well designed passive solar home will reduce monthly heating bills, and initial cost can be partially offset by tax incentives. Federal and state governments allow the builder who uses solar energy to deduct some construction costs from taxable income.

Life Cycle Savings Analysis is useful in determining the advisability of building a solar dwelling. First, the present worth of additional costs for construction, insurance, property taxes and mortgage payments is computed, taking into account inflation and interest rates, over a projected life span, typically 20 or 30 years. Then the same calculations are made for utility savings, tax credits, and tax deductions for additional mortgage interest payments. The Solar Savings is obtained by subtracting the costs from the savings. A negative result indicates that the solar house will be more expensive than a conventional one. A positive result means that, in the long run, the solar house will save the owner money.

Thermal Comfort

What a person perceives as the temperature in a dwelling is actually a function of several factors. The temperature of the air immediately surrounding a body and the velocity of the air past the body affect this perception. Cooler air, and moving air both increase the rate of heat transfer from a warm body to its surroundings. In addition, the humidity of the air is a factor. Moisture in the air decreases the rate of evaporation of sweat, decreasing the heat loss by transpiration cooling. Also, the activity level and the amount of clothing a person wears affects how warm that person feels. The last and perhaps most neglected factor is the temperature of the walls, floor and ceiling. Thermal energy radiated from these surfaces strikes and warms a person. The absence of radiation from a warm wall can easily be detected. Standing in a warm room next to a picture window during the winter, a person will feel colder on the side that is facing the window, for less radiant energy is incident on a body from the cold glass than from a warm wall.

Wray (Ref 7) outlines a method for determining thermal comfort which takes into account all of these factors. In a dwelling, the velocity of air is not sufficient to disrupt natural convection. Therefore, motion of air can be neglected. In addition, for reasons of comfort, the relative humidity must be kept at moderate levels. According to Wray, comfortable equivalent uniform temperatures for

Table II Comfortable Equivalent Uniform Temperatures

Clothing	0% Rel. Humidity Activity Level Office Work	0% Rel. Humidity Activity Level Domestic Work	50% Rel. Humidity Activity Level Office Work	50% Rel. Humidity Activity Level Domestic Work
Light slacks, short sleeve shirt	82 F 28 C	72 F 22 C	79 F 26 C	70 F 21 C
Typical business suit	77 F 25 C	61 F 16 C	75 F 24 C	61 F 16 C

Extracted from: Wray

relative humidities of zero and fifty percent are shown in Table II. The equivalent uniform temperature T_{eu} is the uniform temperature of an imaginary enclosure in which a person will experience the same degree of thermal comfort as in the actual non-uniform environment. For a relative humidity of zero percent,

$$T_{eu} = 0.52\ T_{mr} + 0.48\ T_i \tag{14}$$

where T_{mr} is the mean radiant temperature of the walls, floor and ceiling, and T_i is the interior air temperature. For a relative humidity of fifty percent,

$$T_{eu} = 0.45\ T_{mr} + 0.55\ T_i \tag{15}$$

The mean radiant temperature T_{mr} of the walls, ceiling and floor is the hypothetical uniform temperature of the interior surfaces that would result in the same heat transfer due to radiation to an object in the interior of the room.

Table III Comfort Range ΔT

Clothing	0% Rel. Humidity: Activity Level: Office Work	0% Rel. Humidity: Activity Level: Domestic Work	50% Rel. Humidity: Activity Level: Office Work	50% Rel. Humidity: Activity Level: Domestic Work
Light slacks, short sleeve shirt	5.5 F 3 C	10 F 5.5 C	4.5 F 2.5 C	9 F 5 C
Typical business suit	8 F 4.5 C	14.5 F 8 C	5.5 F 3 C	12.5 F 7 C

Extracted from: Wray

The temperature comfort range centers on the equivalent uniform temperature T_{eu}. According to Wray, a human subject will experience no more than slight discomfort when the equivalent uniform temperature is in the temperature range

$$T_r = T_{eu} \pm \Delta T \tag{16}$$

where T is the comfort range from Table III.

Optimization

Comfort and cost are the overriding factors to be considered in selecting a design for a dwelling. No house that is uncomfortable is worth living in. However, given that the building is designed so an adequate average temperature is maintained, and that the temperature swing is held within tolerances described earlier, the cheapest design will be the best.

III The Computer Model

The approach used to analyse the heat flow in a passive solar structure was to construct an electrical analog circuit. The thermal resistance of the building components were modeled with electrical resistors. Energy storage capability was simulated with capacitors. Heat, then, was the flow between adjacent structural components with different temperatures just as current flows between adjacent nodes with different voltages.

The Circuit Diagram

The circuit diagram for the structure is shown in Fig 4. By analysing the circuit with different values for the resistors and capacitors, and by specifying different values for solar insolation and outside temperature, simulations for a wide variety of structure configurations and sizes can be run for any location across the country and any month of the year. An explanation of each component of the circuit and its real world analog will follow.

The Ambient Temperature T_a. Data available in solar insolation tables include, for each location, average outdoor temperatures, including average highs and lows, for each month of the year. For purposes of the simulation, ambient temperature was approximated by

$$T_a = T_{ave} - T_{swing} \cos((\text{TIME OF DAY} - 2)\pi / 12) \quad (17)$$

where T_{ave} is the mean monthly temperature and T_{swing} is

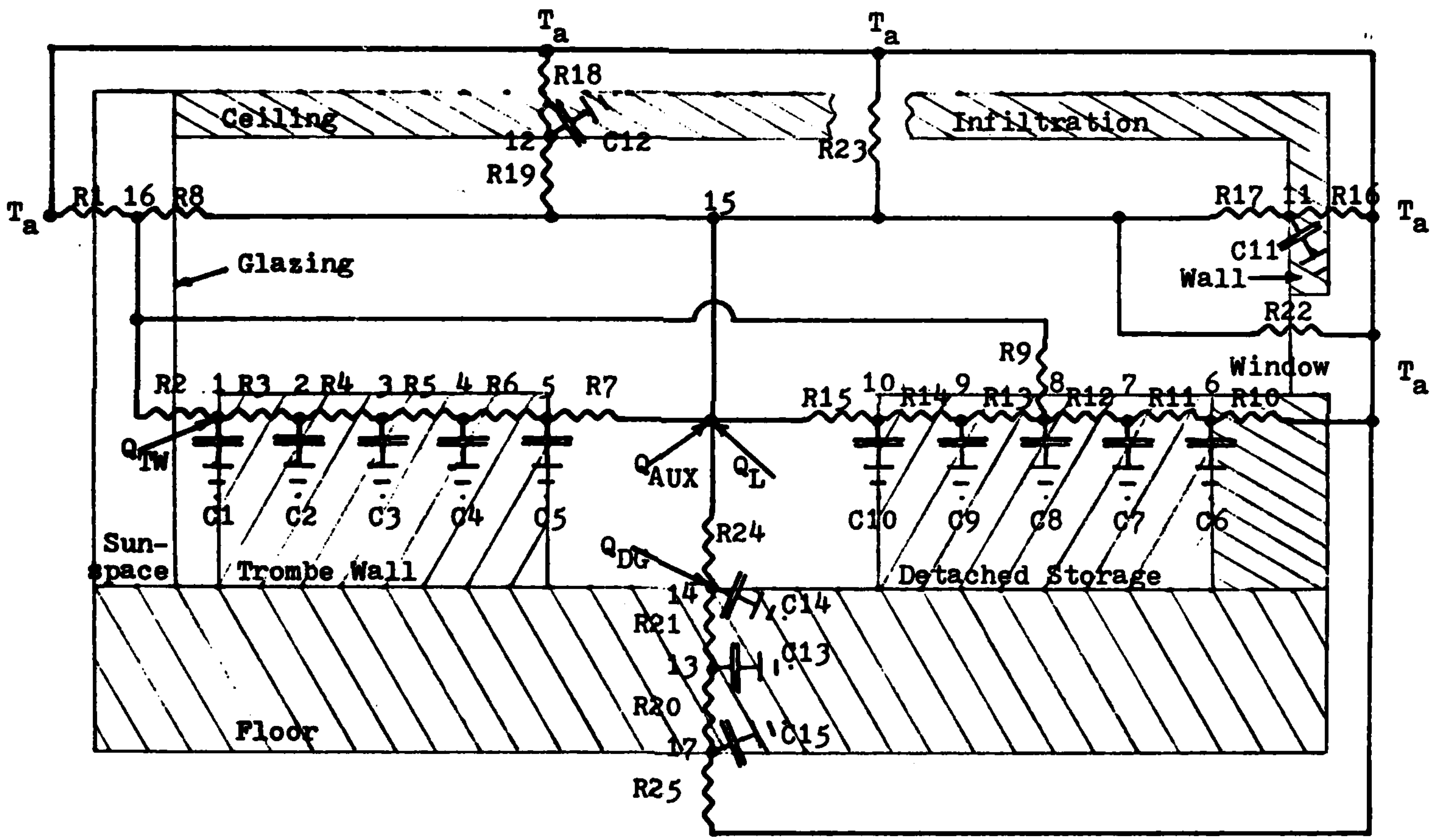

Fig. 4 Schematic and Circuit Diagram for Heat Flow in the Solar Structure

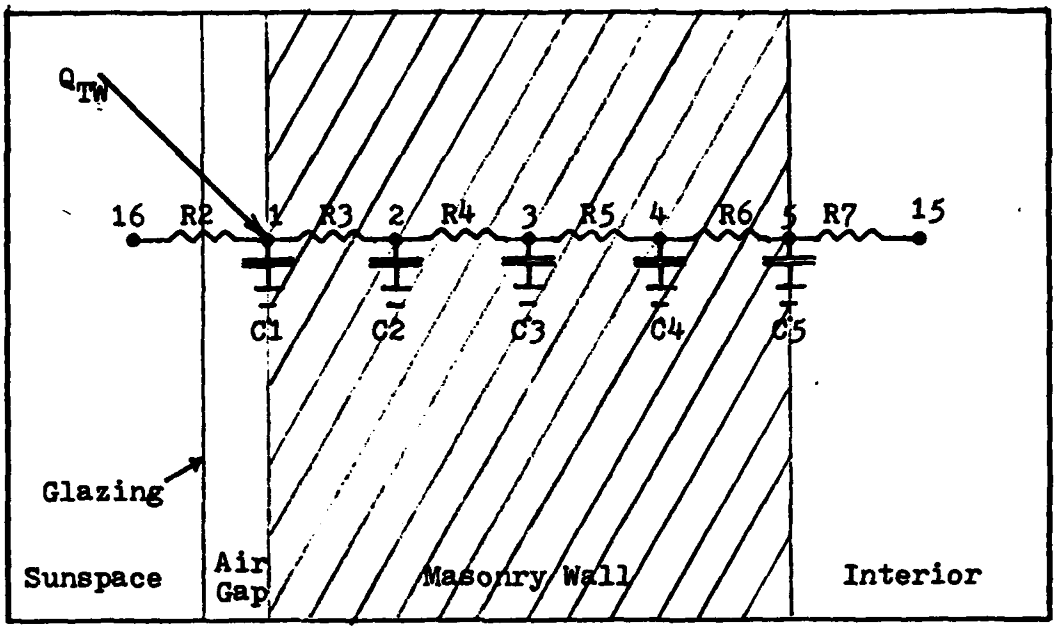

Fig 5. Schematic and Circuit Diagram for Trombe Wall

half the difference between the average high and the average low for that month.

<u>Nodes 1 through 5: Trombe Wall</u>. Refer to Fig 5. Given that the surface area is large compared to the thickness, one dimensional heat flow is a good assumption. According to Duffie and Beckman, heat flow in a thick wall can be adequately modeled with five nodes. Following this suggestion, one node was placed at the outside surface, one at the inside surface, and three equally spaced within. Total heat capacitance of the wall was $C_p \rho V$, where C_p is the specific heat of the masonry, ρ is its density, and V is its volume. Capacitors C2, C3, and C4 were each assigned values of one fourth the total wall capacitance, while capacitors C1 and C5 were each assigned

one eighth the total value. Total internal resistance was given by $k\ V / A_{TW}^2$, where k is the resistance to conduction in the masonry, and A_{TW} is the cross sectional area of the wall. Resistors R3 through R6 were each assigned a value of one fourth the total internal resistance.

Resistor R2 models the combined resistance of the natural convection air film between the sunspace and the glazing, resistance to conduction in the glazing, and insulation provided by the air gaps. Resistor R7 represents the natural convection air film between the wall and the interior air space.

Solar input for the Trombe wall Q_{TW} is added at node 1. The value of this input was calculated using the algorithm detailed in Section II.

Nodes 6 to 10: Detached Storage Mass. As shown in Fig 6, the model for the detached storage mass is very similar to the model for the Trombe wall: five nodes spanning the thinnest dimension (the direction of heat flow). Values for capacitors C6 through C10 and resistors R11 through R14 are calculated the same way as for capacitors C1 through C5 and resistors R3 through R6, respectively. For this model, heated air from the sunspace passes down channels through the center of the storage mass. A good configuration would be blowing air through a cinder block wall with the cavities aligned. For this reason, resistor R9 connects the sunspace with node 8. A method for calculating the value of resistor R9 is shown in Section II. Resistor R10 may be

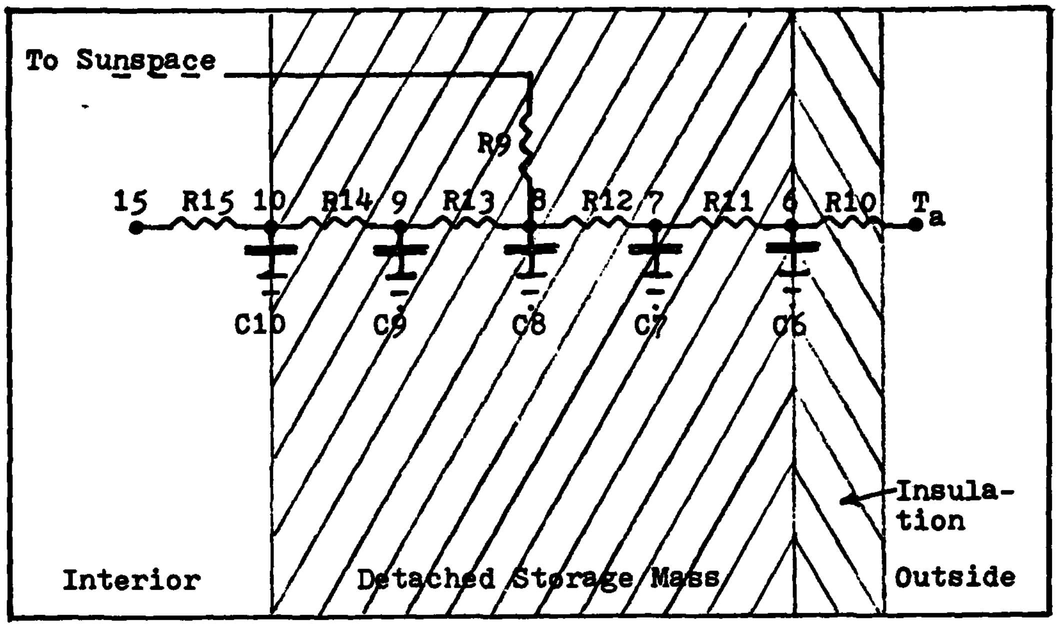

Fig. 6 Circuit Diagram for Heat Flow in the Detached Storage Mass

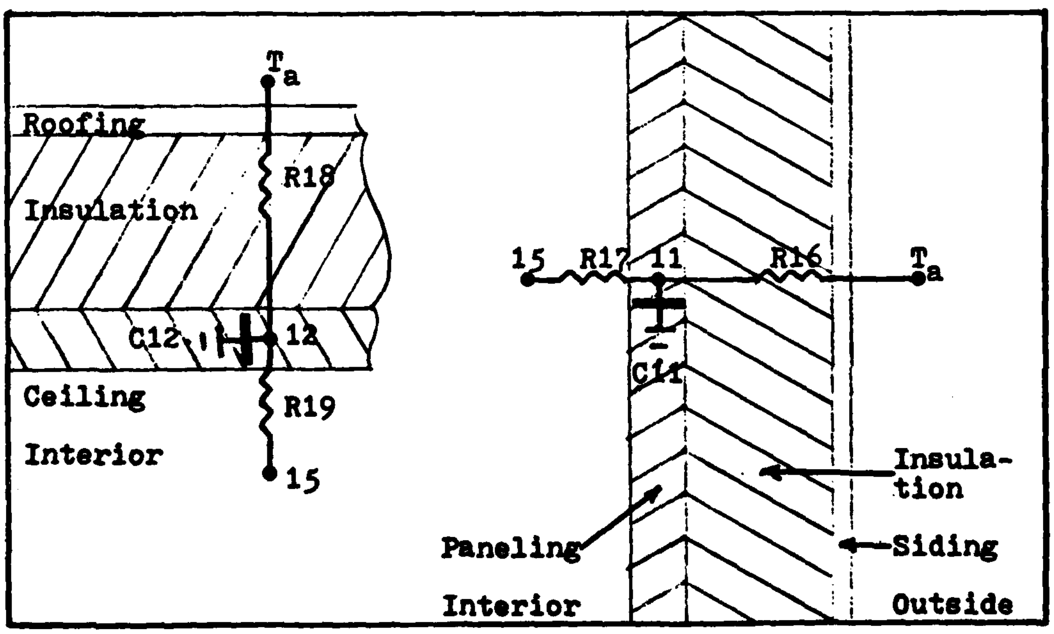

Fig. 7 Circuit Diagram for Heat Flow in a Ceiling/Roof and in a Wall

the perimeter resistance if the detached storage mass is in the floor of the structure; it is the resistance of an outside wall if the storage mass is at the back (north side) of the structure.

<u>Nodes 11 and 12: Outside Walls and Roof/Ceiling</u>. The models for a wall and a roof/ceiling with insulation are shown in Fig 7. Note that mass outside the insulation envelope is not assigned a capacitance. Since structural components outside the insulation are not thermally protected from outside temperatures, these temperatures were considered to be close to ambient temperature. Materials inside the installed insulation were considered to be thermal mass affecting the interior temperature swing, and were considered when calculating the values of capacitors C11 and C12. Values for resistors R16 and R18 were obtained by summing the thermal resistances for the building components involved. Resistors R17 and R19 modeled resistance due to convection air films on the walls and ceiling, respectively. The area for determining the wall capacitance and resistances is the vertical area (product of perimeter length and wall height) less all window area and wall area accounted for by the Trombe wall and or the detached storage mass. The area for determining the roof/ceiling capacitance and resistances is the interior floor area.

<u>Nodes 13, 14, and 17: Floor</u>. This model allows for a masonry or concrete slab floor, perhaps with tile or linoleum covering. The floor, being thinner than a Trombe

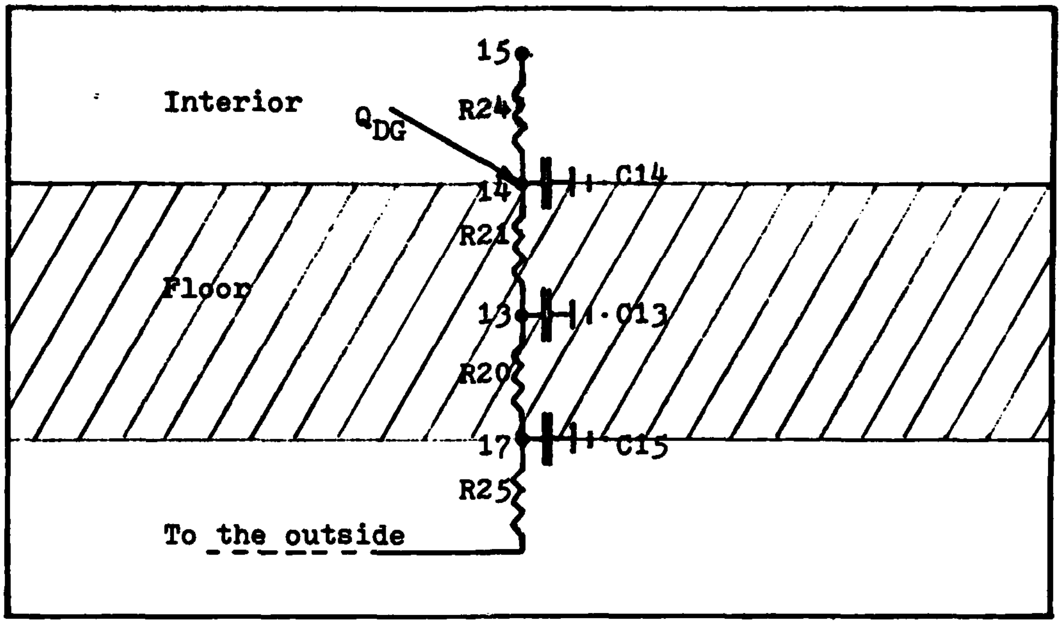

Fig. 8 Schematic and Circuit Diagram for Heat Flow in Floor

wall or detached storage mass, can be modeled with fewer than five nodes. Three nodes were selected, as shown in Fig 8. Values for capacitors C13, C14, and C15 and resistors R20 and R21 are determined in the same manner as for the Trombe wall. Capacitor C13 has a value of one half the total capacitance, while capacitors C14 and C15 each have a value of one fourth. Resistors R20 and R21 are each assigned values of one half the internal resistance of the floor. Resistor R24 is an air film resistance between the floor and the interior, while resistor R25 is the perimeter resistance described in Section II.

The direct gain insolation that enters the structure is absorbed and or reflected by surfaces in the room. Walls, ceiling, furniture, and floor all absorb some portion of

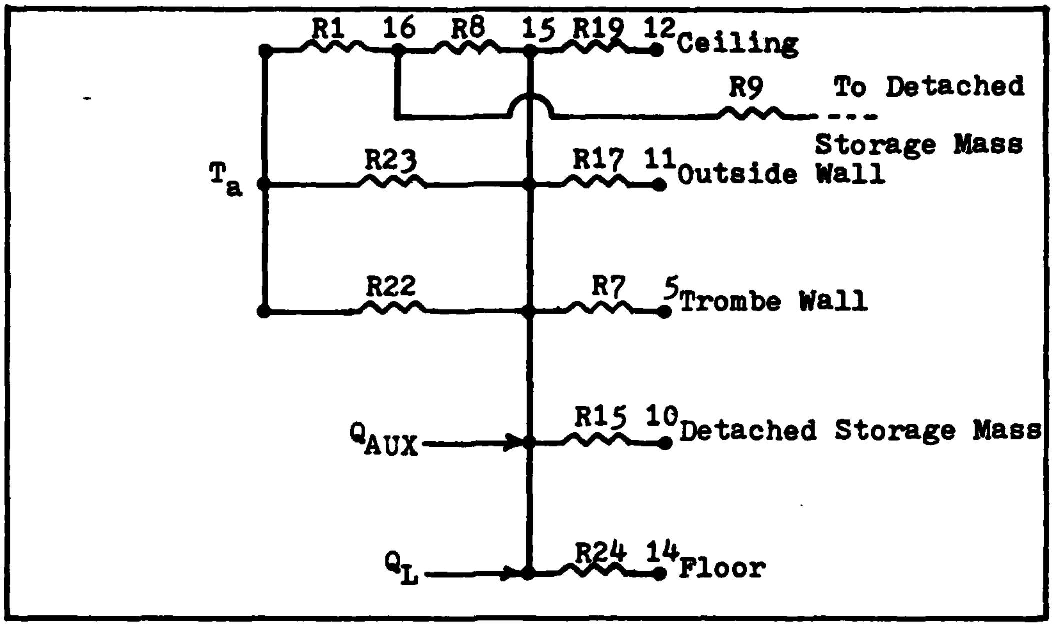

Fig. 9 Circuit Diagram for Heat Flow in Sunspace and Interior

direct gain radiation. However, for most structures, in most locations, for the longest portion of the insolation period, most of the direct radiation is incident on the floor. For this reason, the direct heat gain Q_{DG}, which is calculated using the method described in Section II, is input at node 14.

Nodes 15 and 16: Interior Air and the Sunspace Air. These do not have capacitors associated with them. See Fig 9. While air does have a heat capacitance, it is small compared to that of the thermal mass. Hence, interior air will change temperature much more quickly in response to a given heat input than will building materials in the structure. Resistors R1, R8 and R22 model the thermal resistance

in the glazing between outside and sunspace, between sunspace and interior through the direct gain glazing, and between the interior and outside through non-south windows, respectively. Curtains, night insulation, and shades can affect the value of these resistors. Resistor R23 models the resistance to infiltration described in Section II.

The interior air is heated by convection from warm surfaces such as the interior of the Trombe wall and the floor. Heat gain from appliances Q_L and from the furnace Q_{AUX} also directly heat the air. While heat generated by appliances and people is neglected in this study, the provision for specifying internal loads is included.

Design Choices

Conventional Structures and Direct Gain Systems. Referring to Fig 4, conventional structures and direct gain systems can be modeled by proper selection of resistor values. By setting resistor R1 to a very low value, say 10^{-15}, resistors R2, R7, R9, R10, and R15 to very high values, say 10^{15}, and setting the area of the Trombe wall to zero, the sunspace, Trombe wall, and detached storage mass are effectively eliminated from the circui+. Direct gain solar heating through unshuttered, south facing glazing can then be modeled by making the south facing glazing area small for a conventional house or by making the area large for a direct gain system.

Indirect Gain Systems. Again referring to Fig 4, indirect gain systems can be modeled by setting resistors R8,

R9, R10, and R15 to very high values, and setting the area of the south facing glazing to zero, thereby eliminating the direct gain and detached storage from the circuit. The remaining circuit then models heat flow in a structure with a solar heating system that is exclusively Trombe wall.

To simulate a structure with a sunspace and detached storage mass, and no windows between the sunspace and interior, still other choices are required. The sunspace requires mass to absorb incident radiation and heat the contained air. Mass in the form of a vertical, south facing wall can be modeled. This wall, if thin, can be modeled with node 1. A thicker wall in the sunspace may require use of nodes 2, 3 and perhaps 4 to yield an adequate model. Those nodes in the Trombe wall that are not used to model the sunspace mass must be isolated. A conventional wall used to separate the sunspace from the interior can be modeled by assigning resistor R8 a value appropriate to simulate resistance to heat flow in such a wall. Lastly, if the detached storage mass is also to be the floor of the structure, resistors R24 and R25 must be assigned large values to isolate the three-noded model.

Combination of Features. With imagination, a structure with any combination of the above passive designs may be easily modeled. The engineer can alter his or her design, or alter the proportion of collector dedicated to each type of system to find the most effective design for the location, climate, and intended use of structure.

Night Configuration. During the time the sun is not

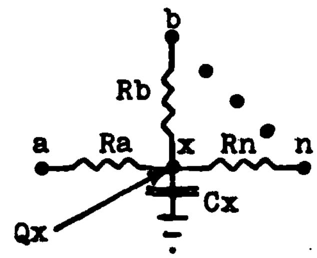

Fig. 10 Circuit Diagram of an Arbitrary Node

shining on the collector, heat is lost through it. Because a large expanse of glass has very low resistance to heat flow, many builders make provisions for insulated shutters, curtains, or shades to be used at night. For this reason, resistor R1 must have a daytime and a nighttime value.

In addition, air flow to the detached storage mass may be cut off at night. Therefore, resistor R9 also must have a daytime and a nighttime value.

The Governing Nodal Equations

Heat flow at each node in the circuit diagram can be described by a governing equation. Consider a general node x attached to capacitor x and connected to an arbitrary number n of nodes as shown in Fig 10. A general heat flow Qx is also input directly to the node. The heat flowing to node x through each resistor Rn is proportional to the temperature difference across the resistor and inversely proportional to the magnitude of the resistance. This is given by

$$\frac{Tn - Tx}{Rn}$$

where Tn and Tx are the temperatures at nodes n and x, respectively. The total heat flux to node x through the resistors and as a result of the direct heat input Qx is

$$Qx + \frac{Ta - Tx}{Ra} + \frac{Tb - Tx}{Rb} + \cdots + \frac{Tn - Tx}{Rn}$$

The rate of rise in temperature at node x is proportional to the total heat flux and inversely proportional to the value of capacitor Cx.

$$\frac{dTx}{d\tau} = \frac{\text{TOTAL HEAT FLUX}}{Cx}$$

where τ is time. Hence, the governing differential equation for node x is

$$Cx\,\frac{dTx}{d\tau} = Qx + \frac{Ta - Tx}{Ra} + \frac{Tb - Tx}{Rb} + \cdots + \frac{Tn - Tx}{Rn}$$

If the value of capacitor Cx is zero, i.e., if node x has no capacitor, then the heat flux to node x must sum to zero. The resulting algebraic equation is

$$0.0 = Qx + \frac{Ta - Tx}{Ra} + \frac{Tb - Tx}{Rb} + \cdots + \frac{Tn - Tx}{Rn}$$

The differential or algebraic equations governing heat flow at each node are listed below.

$$\text{Node 1:}\quad C1\,\frac{dT1}{d\tau} = Q_{TW} + \frac{T16 - T1}{R2} + \frac{T2 - T1}{R3} \qquad (18)$$

Node 2: $$C2\,\frac{dT2}{d\tau} = \frac{T1 - T2}{R3} + \frac{T3 - T2}{R4} \qquad (19)$$

Node 3: $$C3\,\frac{dT3}{d\tau} = \frac{T2 - T3}{R4} + \frac{T4 - T3}{R5} \qquad (20)$$

Node 4: $$C4\,\frac{dT4}{d\tau} = \frac{T3 - T4}{R5} + \frac{T5 - T4}{R6} \qquad (21)$$

Node 5: $$C5\,\frac{dT5}{d\tau} = \frac{T4 - T5}{R6} + \frac{T15 - T5}{R7} \qquad (22)$$

Node 6: $$C6\,\frac{dT6}{d\tau} = \frac{T_a - T6}{R10} + \frac{T7 - T6}{R11} \qquad (23)$$

Node 7: $$C7\,\frac{dT7}{d\tau} = \frac{T6 - T7}{R11} + \frac{T8 - T7}{R12} \qquad (24)$$

Node 8: $$C8\,\frac{dT8}{d\tau} = \frac{T7 - T8}{R12} + \frac{T9 - T8}{R13} + \frac{T16 - T8}{R9} \qquad (25)$$

Node 9: $$C9\,\frac{dT9}{d\tau} = \frac{T8 - T9}{R13} + \frac{T10 - T9}{R14} \qquad (26)$$

Node 10: $$C10\,\frac{dT10}{d\tau} = \frac{T9 - T10}{R14} + \frac{T15 - T10}{R15} \qquad (27)$$

Node 11: $$C11\,\frac{dT11}{d\tau} = \frac{T_a - T11}{R16} + \frac{T15 - T11}{R17} \qquad (28)$$

Node 12: $$C12\,\frac{dT12}{d\tau} = \frac{T_a - T12}{R18} + \frac{T15 - T12}{R19} \qquad (29)$$

Node 13: $$C13\,\frac{dT13}{d\tau} = \frac{T17 - T13}{R20} + \frac{T14 - T13}{R21} \qquad (30)$$

Node 14: $$C14\,\frac{dT14}{d\tau} = Q_{DG} + \frac{T15 - T14}{R24} + \frac{T13 - T14}{R21} \qquad (31)$$

$$\text{Node 15:}\quad 0.0 = Q_L + Q_{AUX} + \frac{T5 - T15}{R7} + \frac{T16 - T15}{R8} + \frac{T14 - T15}{R24} + \frac{T10 - T15}{R15} + \frac{T11 - T15}{R17} + \frac{T12 - T15}{R19} + \frac{T_a - T15}{R22} + \frac{T_a - T15}{R23} \quad (32)$$

$$\text{Node 16:}\quad 0.0 = \frac{T_a - T16}{R1} + \frac{T1 - T16}{R2} + \frac{T15 - T16}{R8} + \frac{T8 - T16}{R9} \quad (33)$$

$$\text{Node 17:}\quad C15\,\frac{dT17}{d\tau} = \frac{T_a - T17}{R25} + \frac{T13 - T17}{R20} \quad (34)$$

The Computer Program

The computer program solves the differential and algebraic equations numerically, using an Euler method predictor, and a trapezoid rule corrector. The programmer selects the time step increment and the total number of hours that are to be simulated. The program will set the time of day to midnight and then calculate the temperature of each node at each increment of time. Print-out includes nodal temperatures, as well as the computed values of outside temperature, solar direct gain and indirect gain heat inputs, and any heat added by the furnace and internal equipment. Even though this study does not include heat from internal equipment, the provision is in the program. One line is printed for each time increment. A listing of the program along with an explanation of the variables and information on required data input comprizes Appendix A.

IV Model Verification

At the Los Alamos National Laboratory in Los Alamos, New Mexico, McFarland (Ref 8) oversaw a project to collect data on energy flow in buildings passively heated by the sun. Fourteen separate 400 ft^3 cells were constructed, each with a different design for solar gain. Every cell had a collector area of 23.4 ft^2 and faced directly south. The cells were instrumented with thermocouples at important locations and equipped with a 600W heater (6 100W light bulbs) to maintain a minimum interior temperature of 65 F. Temperatures in the cells, and the energy used by the heater in each cell, as well as ambient temperature, solar insolation and wind conditions were recorded each hour for the winter of 1980-81.

Test Cell Simulated

Test cell #1 was of 2X4 frame construction with fiberglass and polystyrene insulation. Plywood covered the floor and the outside walls. The cell was equipped with a concrete, unvented Trombe wall behind a double glazed aperture. The Trombe wall was 15-5/8 in. thick with its south facing surface painted flat black. Forced ventilation maintained an infiltration rate at a steady 3 complete air changes per hour. The cell was constructed to have a Building Load Coefficient (BLC) of 26 B/hr-F, that is, to have a heat loss of 26 B/hr for every degree temperature difference between the inside and outside. Cell #1 had thermocouples

placed in the center of the interior and also at three locations on the Trombe wall: the south surface at mid-height, the center, and the north surface at mid-height. Cell #1 was modeled so that these locations corresponded to nodes 15, 1, 3, and 5, respectively. Conditions on 14 December 1980 were simulated. Details of construction, along with calculated input information for the computer program is given in Appendix B.

Computer Program Modifications

The computer program calculates hourly insolation rates on a vertical surface given monthly-average daily total radiation on a horizontal surface. In addition, the program estimates outside temperatures from monthly averages. However, data collected at Los Alamos included hourly total radiation on a vertical surface I_{tv} and on a horizontal surface I, and the outside temperature. The computer program was modified to read in hourly insolation and ambient temperature at each simulation time step rather than estimate hourly values from monthly data.

On a clear day, according to Duffie and Beckman, the amount of diffuse hourly sky radiation I_d is given by

$$I_d = 0.177\ I \tag{35}$$

The hourly beam radiation on a vertical surface I_{bv} is the total hourly radiation I_{tv} less all diffuse sky and ground radiation.

$$I_{bv} = I_{tv} - I_d / 2 - \rho_g I / 2 \tag{36}$$

The heat gain at the outside surface of the Trombe wall is then given by

$$Q_{TW} = A_{TW}(I_{bv}\tau\alpha_b + (I_d + \rho_g\ I_t)\tau\alpha_d\ /\ 2) \tag{37}$$

<u>Results</u>

The outside temperature measured in Los Alamos, along with the measured interior temperature and the interior temperature calculated by the simulation are shown in Fig 11. The actual and simulated furnace output required to maintain the interior temperature is graphed in Fig 12. While the interior temperature was closely maintained by the computer program, difficulty was encountered duplicating the furnace behavior. The size of the simulation time step was 0.25 hr. When conditions required that the furnace be turned on in the simulation, the furnace ran for a minimum of 15 minutes. The furnace output rate was 2047 B/hr (600 W), so 512 B was input during each time step that the furnace was running. This was far in excess of requirements and the simulated interior temperature rose too high during the quarter hour that the furnace was running. In the test cell at Los Alamos, the heater cycled as necessary to maintain the interior temperature, probably switching on and off several times every 15 minutes. As the furnace running time in the simulation could not be decreased without lengthening the computer processing time enormously, the furnace output rate was decreased by trial and error to 900 B/hr, presuming that the furnace would

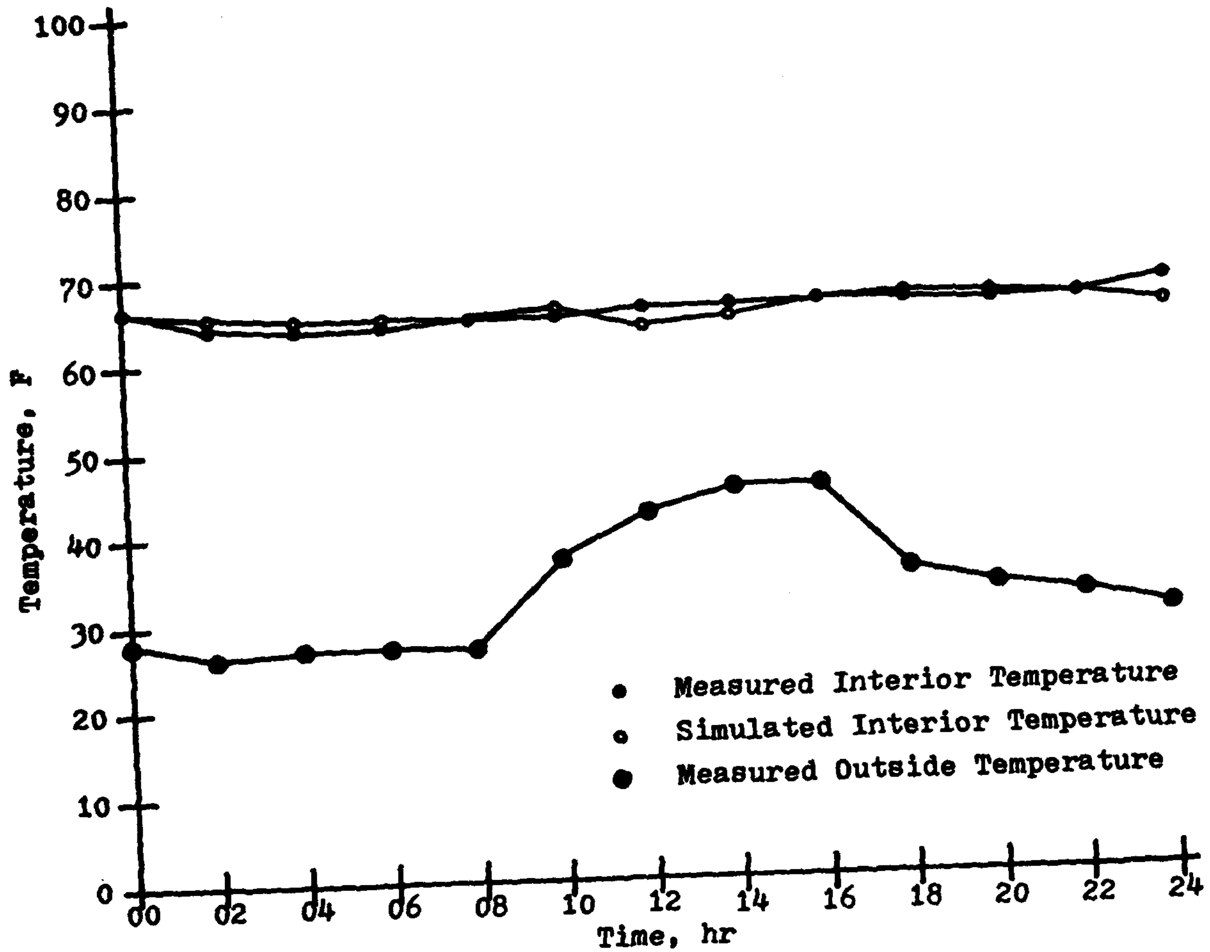

Fig. 11 Interior and Exterior Temperatures

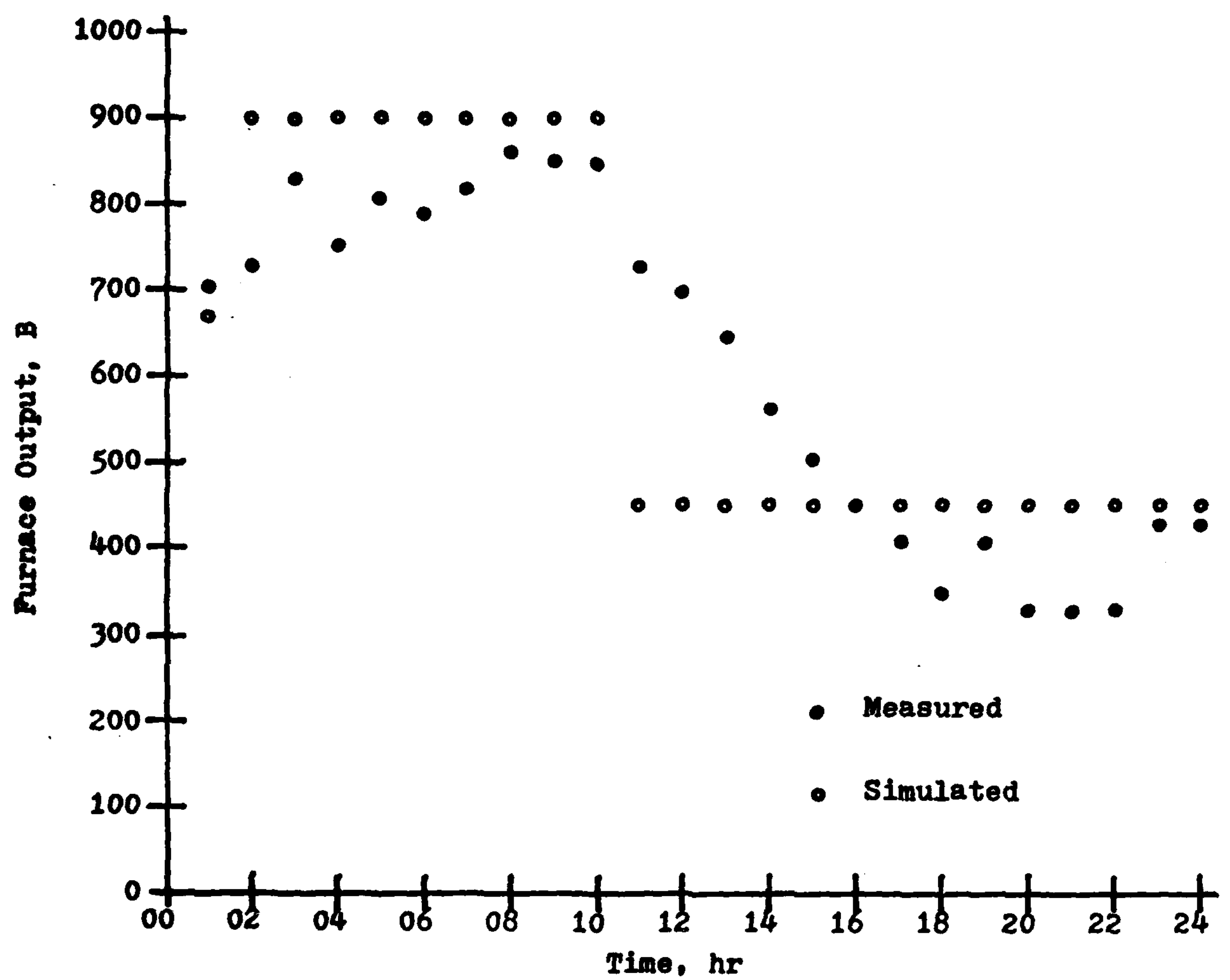

Fig. 12 The Hourly Furnace Output Required to Maintain the Interior Temperature

cycle several times to generate 900 B in 1.0 hr, or 225 B in 0.25 hr. Still, with only 4 time steps in each hour, the simulation had only 4 opportunities to run the furnace each hour. Hence, over the entire hour, only 5 different values for simulated furnace output were possible: 0, 225, 450, 675, and 900 B. Despite the crude approximation, the total auxiliary energy required for the 24 hr simulation was 15075 B, within 4 percent of the value measured in Los Alamos: 14543 B.

Temperatures for the Trombe wall are recorded in Figs 13, 14, and 15. The simulated thermal behavior of the wall was very similar to the instrumented wall in Los Alamos. Temperatures rose and fell at the same times at the same locations in the wall. Simulated temperatures, however, fell slightly faster during the early morning and did not rise as quickly under the influence of solar heating. The maximum difference between measured and simulated temperatures was at node 1, the south surface of the wall, at peak temperature. The spread was 14 F. The overall measured temperature swing was from 63 F to 138 F, or 75 F. The simulated swing was from 61 F to 124 F, or within 16 percent of measured values. After 24 hours, the differences at the three locations were 4 F at the south surface and center, and 5 F at the north surface of the wall.

Part of the temperature differences at node 1 can be explained by the simplicity of the model. The entire mass of the Trombe wall is lumped into 5 capacitors. Node 1 contains 1/8 of the total mass. Hence, the average temperature

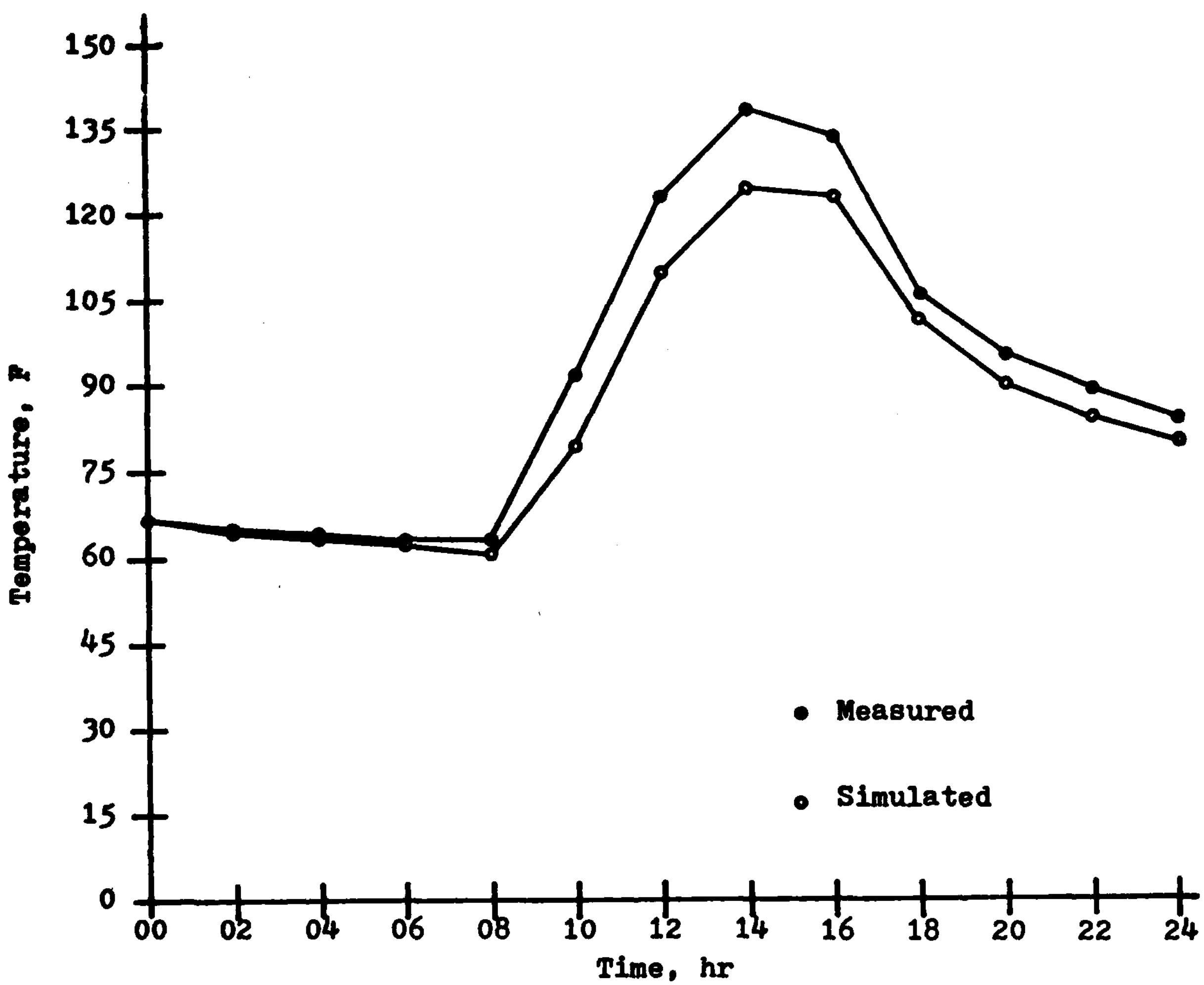

Fig. 13 Temperature of the South Surface of the Trombe Wall

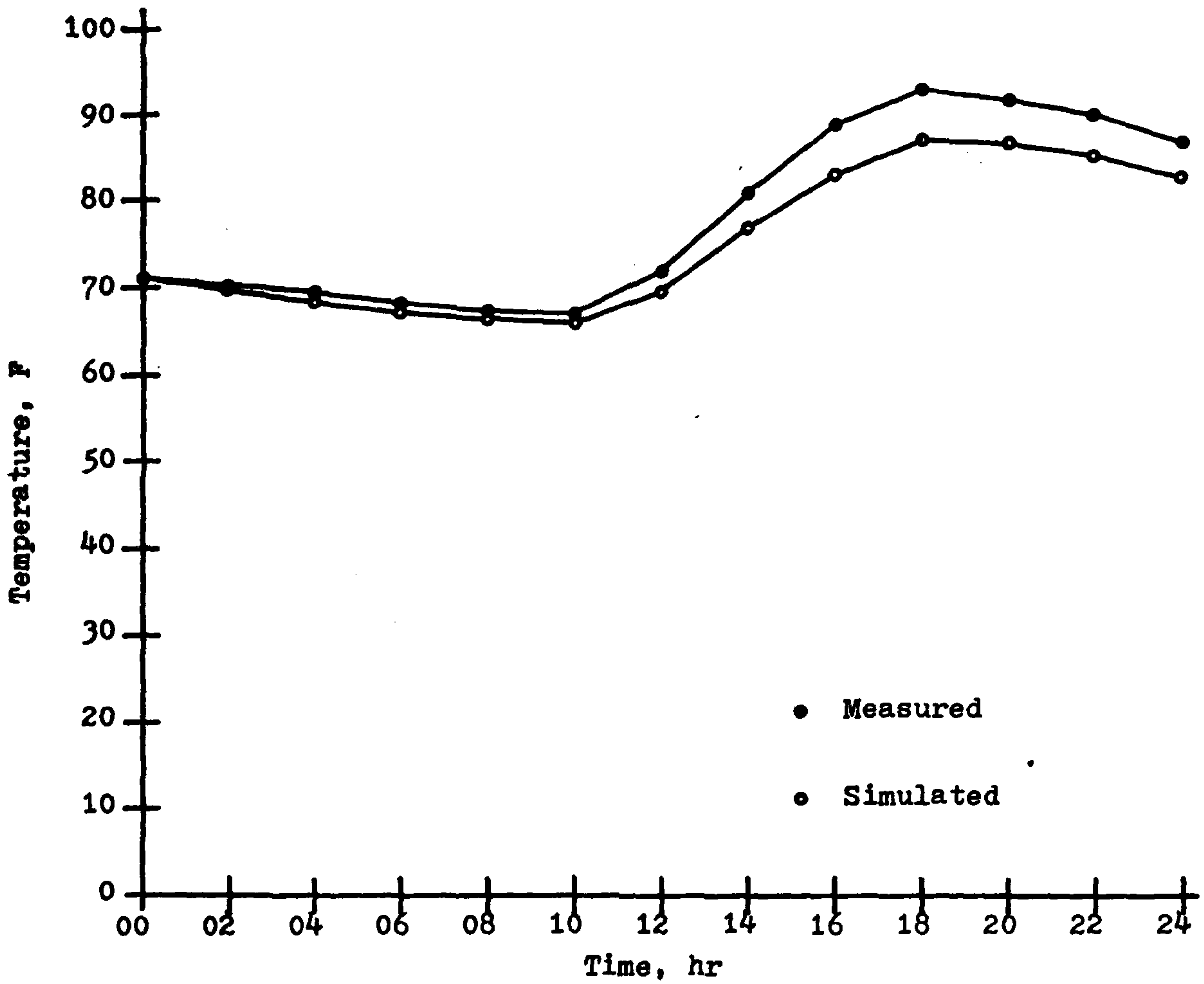

Fig. 14 Temperature of the Center of the Trombe Wall

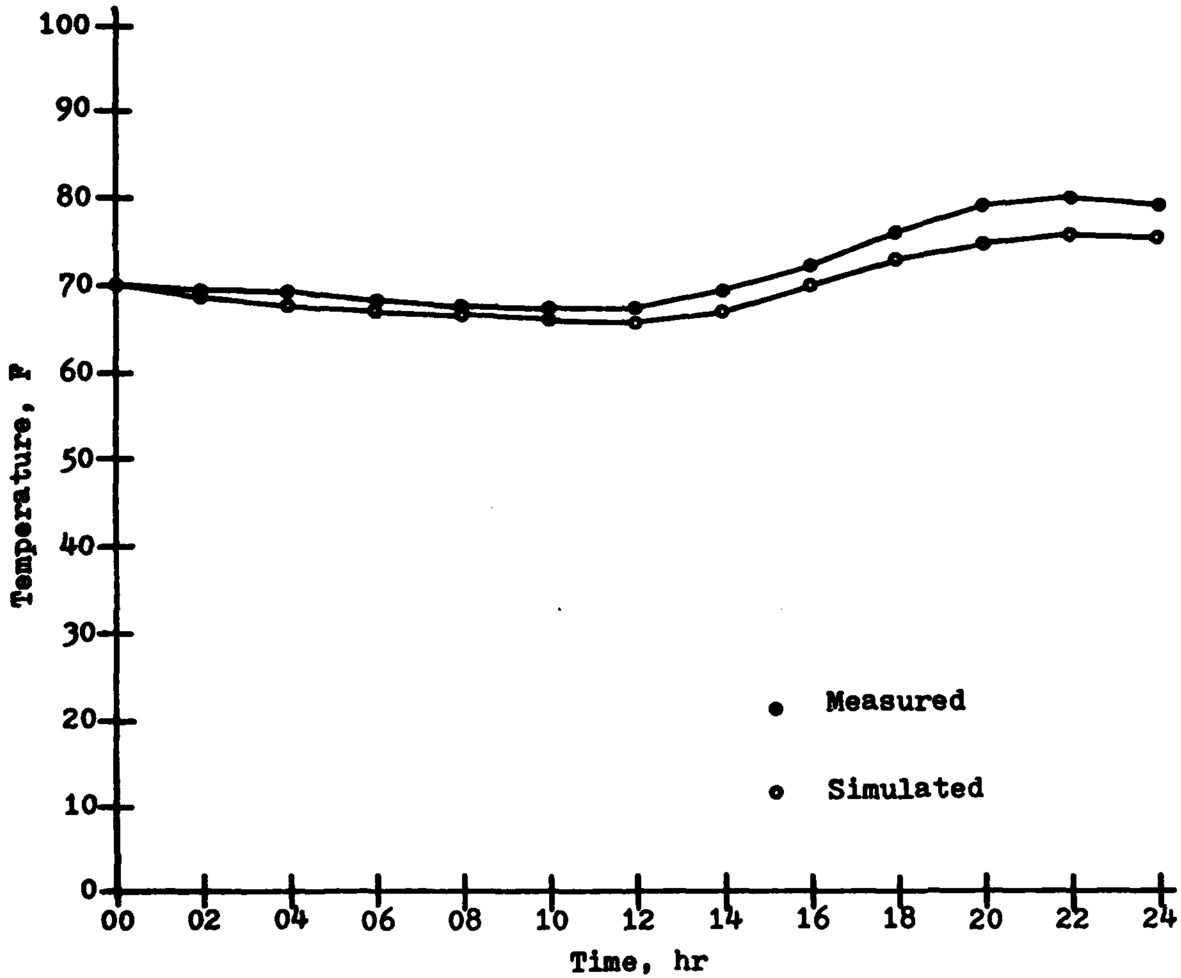

Fig. 15 Temperature of the North Surface of the Trombe Wall

of the outside 1-61/64 in. thickness of the wall was reported for node 1, rather than the surface temperature. This does not explain all the difference between simulated and measured temperatures, for, after the sun went down the surface temperature would drop below the average temperature of the first 1/8 thickness; this cross over did not take place.

Other possible sources of error exist with the computer program and with the data taken at Los Alamos. Much of the input information for the computer program is estimated. For example, R values for insulation are nominal, rather than exact, and are affected by humidity. The resistance due to natural convection air films can also only be estimated. The first order equation solver used by the program can introduce errors at each time step. In Los Alamos, thermocouple output can vary. The pyranometers used to measure solar radiation can have calibration shifts. Even if a high quality pyranometer is frequently calibrated, errors in long term readings can be well over 5 percent. McFarland did not discuss possible errors in pyranometer or thermocouple measurements.

Refer to Figs 5, 13, and 15. If the capacitance and internal resistance of the Trombe wall has been accurately calculated, the slightly faster temperature drop at nodes 1 and 5 before the sun came up could be caused by underestimating the values of resistor R2, the resistance to heat flow from the south surface of the masonry through the double glazing to the outside, and resistor R7, the resistance due to the natural convection air film on the inside of the Trombe wall. To illustrate the sensitivity of the computer

program to the errors discussed above, the simulation was rerun with the values of resistors R2 and R7 increased 10 percent, and the value of hourly solar radiation increased also by 10 percent. The results are shown in Figs 16, 17, and 18. There was no change in the furnace output, and insignificant change in the interior temperature, so these were not regraphed. The increase in resistors R2 and R7 did not significantly alter the behavior of nodes 1 and 5 before the sun came up, although simulated temperatures approximated measured temperatures much more closely. This indicates that the computer model is not very sensitive to errors in the estimation of these resistors. The marked change in the difference between measured and simulated temperatures during the period of solar gain indicates that the model is sensitive to errors in solar input. The maximum difference between simulated and measured temperatures at node 1, the south surface of the Trombe wall, dropped from 14 F to 6 F. The simulated swing was within 7 percent of the measured swing. Temperature differences at the end of the simulation were zero at the south surface of the wall, and 1 F at the center and north surface.

In summary, the computer model does a good job at predicting the furnace energy required for a 24 hour period, but cannot follow hourly trends. In order to predict temperature trends accurately, care must be taken in estimating thermal parameters and inputs.

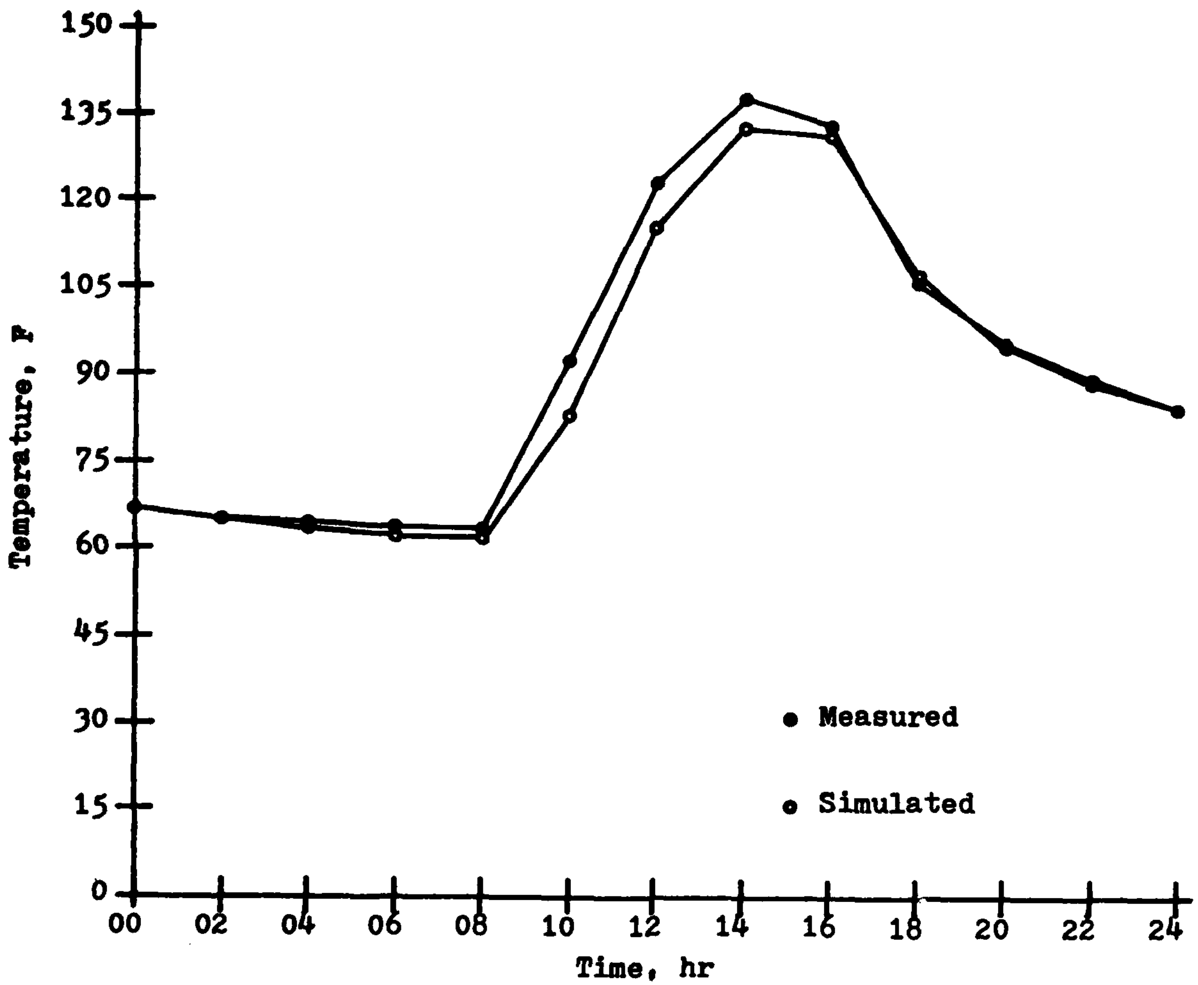

Fig. 16 South Surface of the Trombe Wall for the Modified Simulation

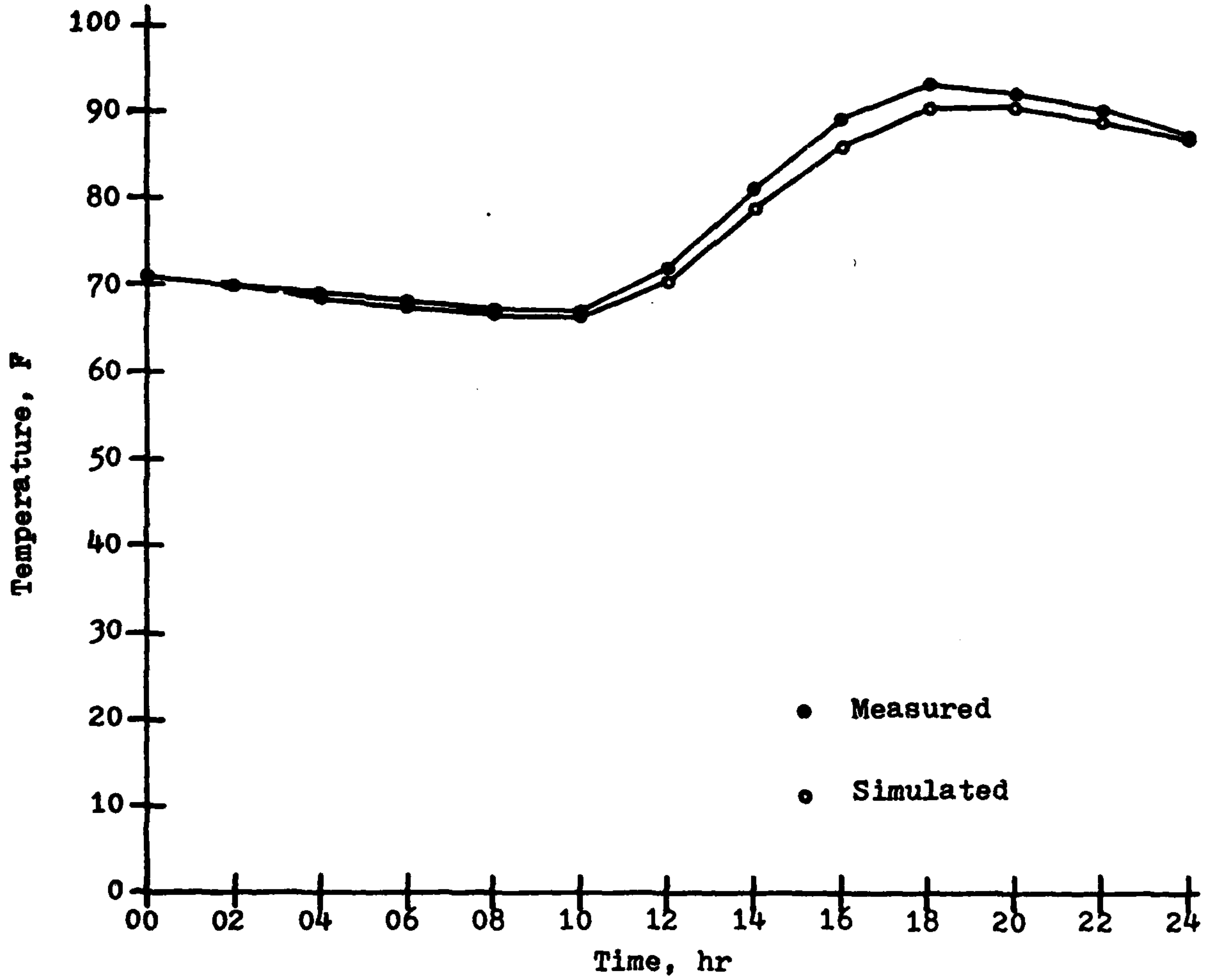

Fig. 17 Center Trombe Wall for the Modified Simulation

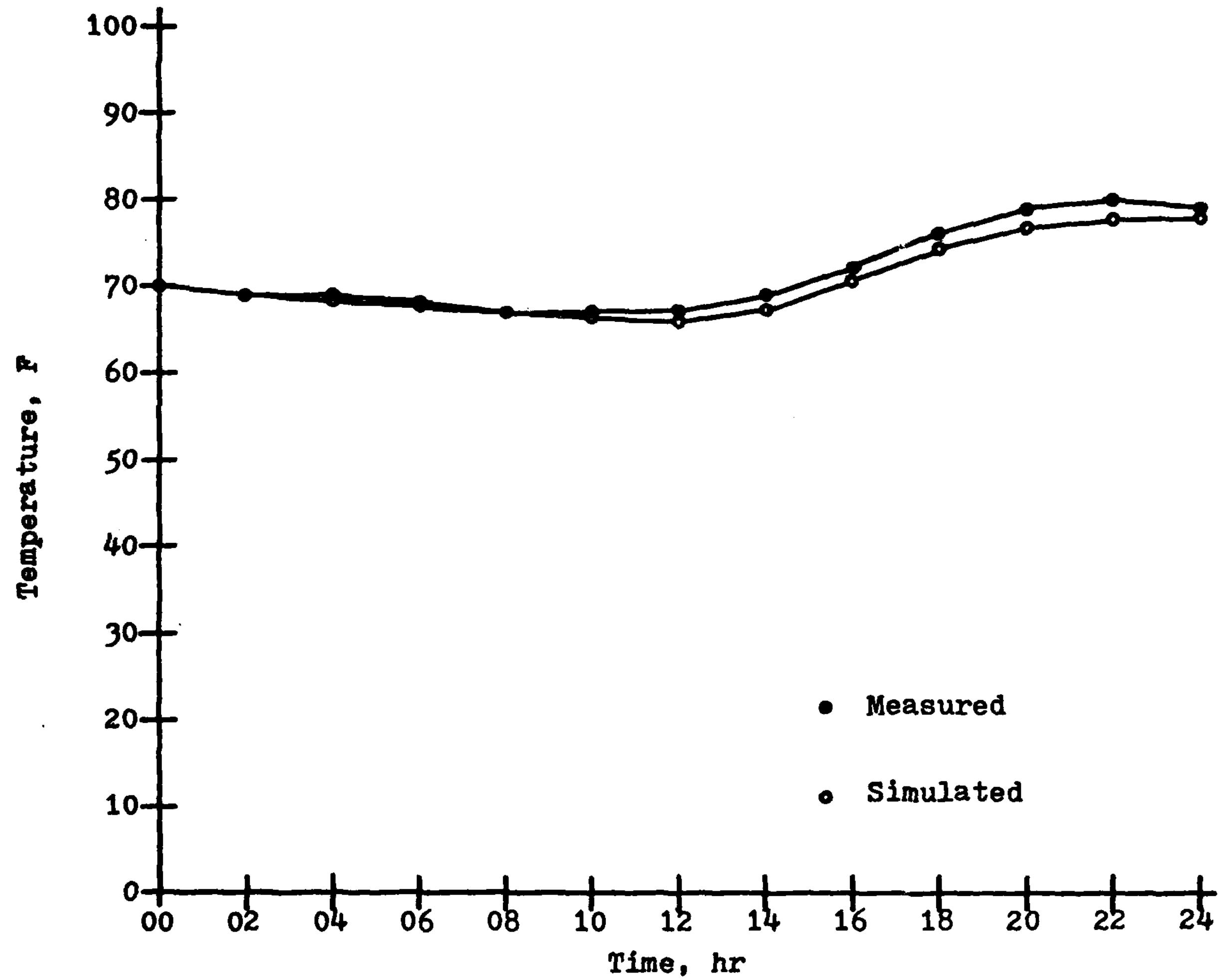

Fig. 18 North Surface of the Trombe Wall for the Modified Simulation

V Example Analysis

To illustrate the usefulness of the computer program in analysing thermal performance of a passive solar design, consider the following hypothetical situation. An agency is considering construction of a 1500 ft^2 structure in Columbus, Ohio to be heated for office activities. Insulation for the building is to be in accordance with guidelines set forth in Mazria. The building is to be 50 ft by 30 ft with an 8 ft ceiling. One 50 ft wall will face directly south. R19 insulation will be installed in the walls, and R34 in the ceiling. Perimeter insulation, valued at R10 will protect the 6 in. thick concrete slab floor by extending 2 ft below ground level. Infiltration will be kept to 3/4 of an air change each hour. Window area will be 150 ft^2, distributed evenly around the walls. All openings will be double glazed. Details of construction and computer input information is presented in Appendix C.

To obtain the annual thermal performance of this conventional structure, a simulation was run for an average day of each month. The total furnace heat output for each day was multiplied by the number of days in the month, then the products summed. The results, along with appropriate heating bills in Columbus, Ohio in 1980 for a gas furnace (78 percent efficient) and for an electric furnace (100 percent efficient) are shown in Table IV.

As an alternative to conventional construction, the

Table IV Monthly Furnace Output for Conventional Structure

Month	Output, 1000 B	Gas Bill, $	Electric Bill, $
Jan	9610	42.10	130.76
Feb	7980	34.96	108.58
Mar	6510	28.52	88.58
Apr	3750	16.43	51.03
May	1240	5.43	16.87
Jun	0	0	0
Jul	0	0	0
Aug	0	0	0
Sep	450	1.97	6.12
Oct	1860	8.15	25.31
Nov	5550	24.31	75.52
Dec	8835	38.70	120.22
Total	45785	200.57	622.99

agency is considering implementing a rule of thumb developed by Balcomb for Columbus, Ohio which recommends installing a passive solar collector in the south wall with an aperture area no greater than 28 percent of the floor area. According to the rule, larger apertures or poorly designed systems with this large an aperture would be prone to overheating on a clear sunny winter day. The collector area for a 1500 ft^2 floor area should be no greater than 420 ft^2. The design under consideration is a structure similar to the conventional one, but with the entire 50 ft by 8 ft south wall built as a collector. The collector

will be triple glazed and will be partly unvented Trombe wall and partly direct gain. Non-south window area will be 75 ft^2, double glazed, and distributed evenly about the non-south walls. R9 night insulation will be available for installation on the outside of the triple glazing.

Three questions arise concerning the thermal performance of the design. How should the collector be split up between direct and indirect gain systems to save the most on the heating bills? Should night insulation be used? Finally, if subjected to a series of consistently sunny days, will the design overheat? To find answers to these questions, a simulation was run for each month of the year for a collector that was 10 percent Trombe wall, 90 percent direct gain. Four other simulations were run with indirect to direct gain ratios of 30/70, 50/50, 70/30, and 90/10. Results of the 50/50 simulation are shown in Table V. For comparison, the empirical SSF method was applied to the 50/50 simulation. Results are in the same table. Annual savings for all 5 designs, with and without night insulation installed when the sun went down and removed when the sun came up are graphed in Fig 19.

Before a direct comparison of the Solar Savings Fraction as calculated from the simulation and developed by the SSF method is made, the question of overheating should be discussed. The simulations run to obtain the results in Table V and Fig 19 were for average days in each month. These days were neither completely sunny nor cloudy. If the design structure were to be subjected to clear, sunny

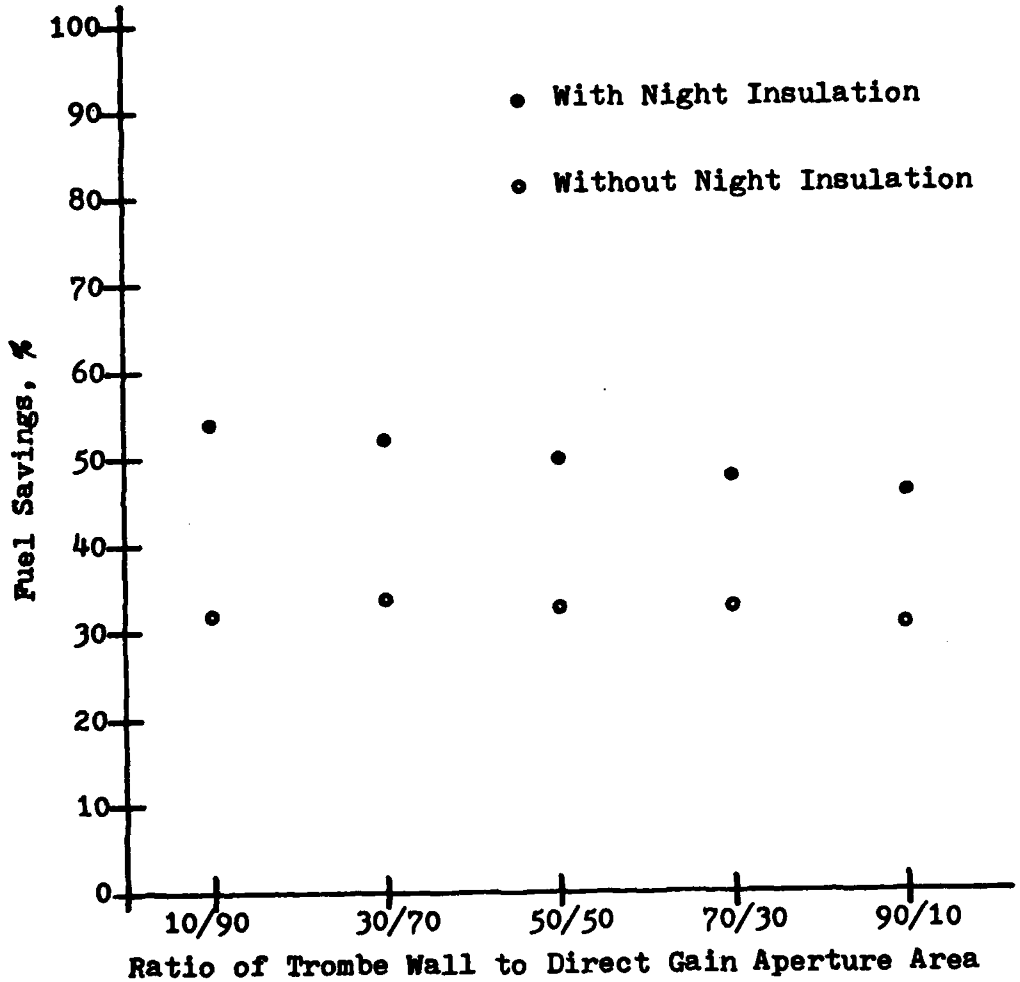

Fig. 19 Annual Decrease in Furnace Output for Passive Solar Designs

Table V Furnace Output and Fuel Savings for the 50/50 Passive Solar Design

	Without Night Insulation			With Night Insulation		
	Simulation		SSF Method	Simulation		SSF Method
Month	Output 1000 B	Savings %	Savings %	Output 1000 B	Savings %	Savings %
Jan	6975	27	-6	5735	40	29
Feb	5460	32	0	3780	53	36
Mar	3565	45	6	2480	62	47
Apr	3750	0	29	3300	12	67
May	930	25	66	465	62	90
Jun	0	-	-	0	-	-
Jul	0	-	-	0	-	-
Aug	0	-	-	0	-	-
Sep	0	100	100	0	100	100
Oct	0	100	62	0	100	88
Nov	3150	43	8	1950	65	49
Dec	6665	25	-10	5115	42	28
Total	30495	33	8	22825	50	44

days, the furnace output for those days would be less than for an average day. If the conditions were too sunny, the interior temperature might climb uncomfortably high.

As an example, a simulation was rerun for each design, with and without night insulation, for a 24 hour period following 5 consistently sunny days in January. The monthly average clearness index $\bar{K}_T$ for January in Columbus, Ohio is

0.356. According to Liu and Jordan (Ref 9), on a clear day the daily total radiation can be 2.4 times greater than the monthly-average daily total radiation. Therefore, 1102.6 B/ft^2-day, rather than the monthly-average of 459.4 B/ft^2-day was input in each simulation for the daily total radiation $\bar{H}$. Figures 20 and 21 contain plots of interior temperature for the 5 designs. Table VI lists, for each design, the extreme interior temperature swing, and for peak conditions, the interior air temperature T_i, the mean radiant temperature T_{mr} for an object in the center of the interior, and the equivalent uniform temperature T_{eu} at 50 percent relative humidity.

For office activity while wearing a typical business suit in 50 percent relative humidity, the comfortable temperature range from Tables II and III is 69.5 to 80.5 F. Subtracting 7 degrees from this range to account for internally generated energy, the design comfort range becomes 62.5 to 73.5 F. The extreme allowable temperature swing is 11 F. For simulations of designs without night insulation, only the 70/30 case and the 90/10 case keep the temperatures within the comfort range. None of the cases where night insulation is used have a peak temperature within the comfort range. The primary conclusion that can be drawn from this information is that, for most of the designs, excess energy will have to be vented to prevent overheating on a sunny day. The energy dump will result in a decrease in the overall monthly solar savings.

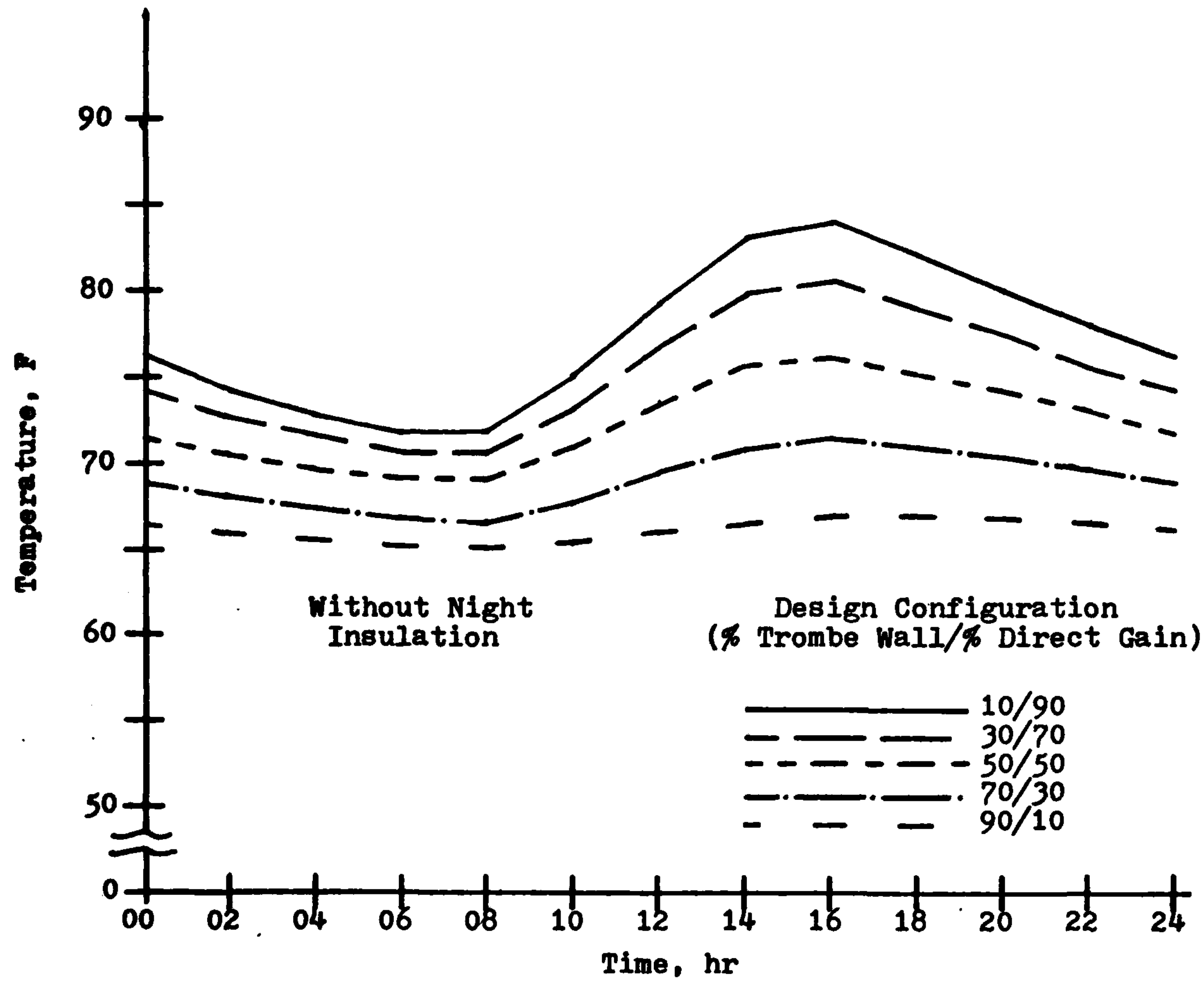

Fig. 20 Interior Temperature Swings for a Sunny Day in January

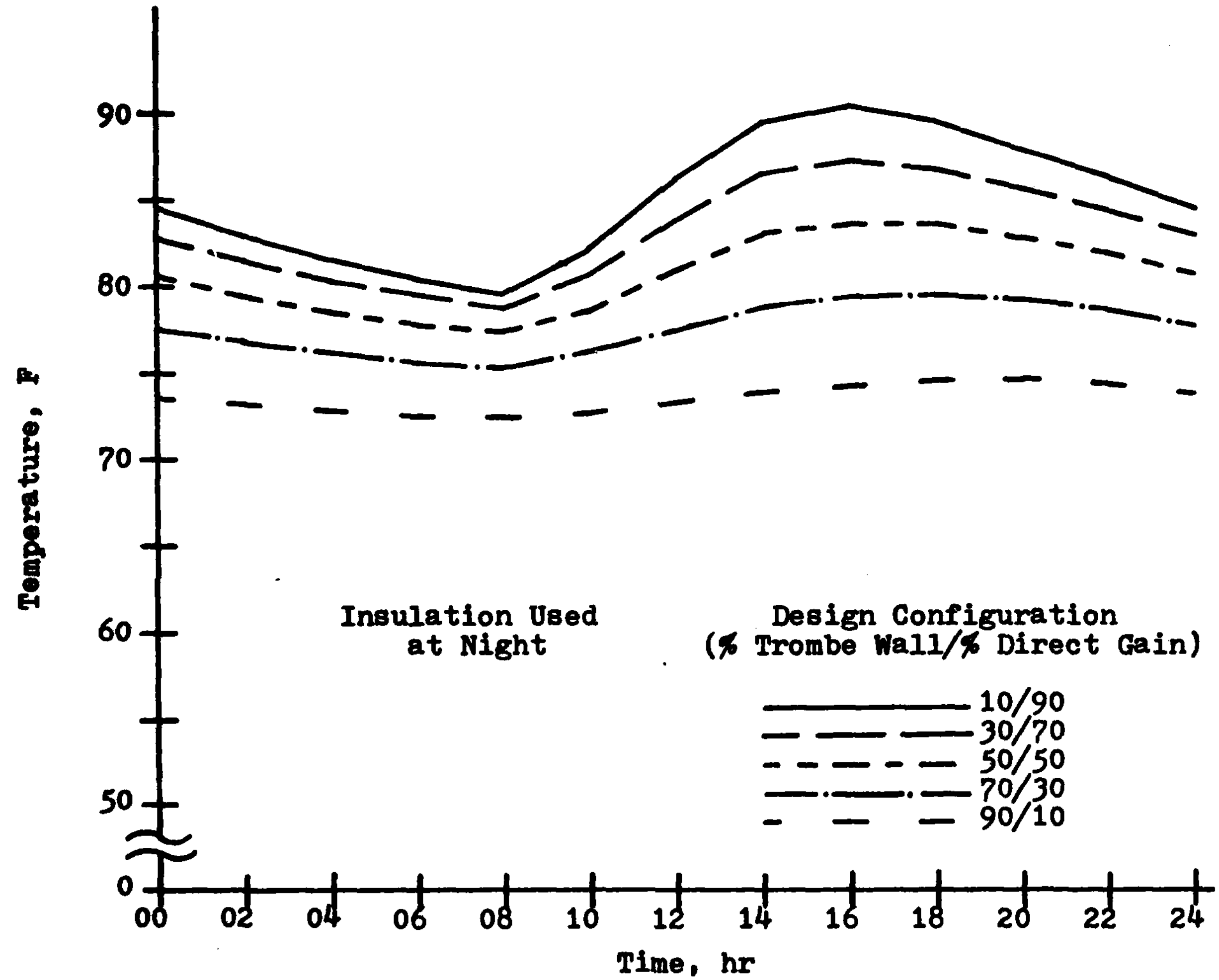

Fig. 21 More Interior Temperature Swings for a Sunny Day in January

Table VI The Peak Interior Temperature on a Sunny Day

Indirect to Direct Gain Area Ratio	Night Insulation	Temperature Swing, F	T_i, F	T_{mr}, F	T_{eu}, F
10/90		12.8	84.2	82.4	83.4
10/90	X	11.2	90.4	88.4	89.5
30/70		10.2	80.5	79.4	80.0
30/70	X	9.0	87.4	85.4	86.5
50/50		7.5	76.2	75.7	76.0
50/50	X	6.8	83.9	82.7	83.4
70/30		4.8	71.4	71.5	71.4
70/30	X	4.4	79.6	79.3	79.5
90/10		1.9	66.9	67.6	67.2
90/10	X	2.1	74.5	75.3	74.9

Nonetheless, there is not a strong correlation between the savings computed by the simulation and by the SSF method, despite the capability of the program to closely depict the performance of the Los Alamos test cell. Using the simulation values as a base, the annual savings predicted by the empirical method differed by as much as 76 percent.

VI Conclusions and Recommendations

The objective of this study was to create a small computer simulation program that is quick and easy to use, yet can predict with reasonable accuracy a temperature swing and energy savings. It appears that a useful tool has been devised. Favorable correlation with test cell experiments in Los Alamos, New Mexico was achieved. There is weaker correlation with results derived using the empirical SSF method. As pointed out in Ref 3, the DOE2 simulation program also produces results different from the SSF method. This warrants further investigation. There are data for 13 more test cells in the Los Alamos study, and data for many more days than the day simulated for test cell #1. It is strongly recommended that this data be used for further verification studies. Then, the program should be used as a tool for a real, perhaps local, design project.

While the program is simple and requires little computer time, it is not the best possible model. Additional features, such as the ability to "open a window" when the interior temperature gets too high, the ability to investigate solar cooling, and the ability to specify overhangs for shading would make the program much more useful. It is recommended that these features be added to the program.

The transient simulation program was written for use on the new micro-computers. The final recommendation is that a project to adapt the program to such a piece of hardware be undertaken.

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Appendix A

This appendix contains the computer program used to simulate heat flow in a structure heated passively by the sun. The program is written in PASCAL. Following the source code listing is an explanation of the significant variables used in the program. Finally, a list of input information in required order is presented.

```
PROGRAM SOLHUT (INPUT,OUTPUT);
(*A PROGRAM THAT MODELS THE HEAT FLOW IN A RESIDENTIAL STRUCTURE*)
(*THAT IS PASSIVELY HEATED BY THE SUN. FEATURES OF THIS STRUCTURE*)
(*INCLUDE HEATING BY DIRECT GAIN, TROMBE WALL, ANDOR TRANSFER TO*)
(*INSULATED MASS STORAGE*)
 TYPE
      VECTORTYPE=ARRAY[1..17] OF REAL;
 VAR
 (*ARRAYS*)
      T,TI,TP,TC,DT,DTD:VECTORTYPE;
 (*REALS*)
      NC,SINTHETAC,THETAC,THETA,RHO1,RHO2,KAPPA,THICKGLAS:REAL;
      DTV,DDG,DDGNEXT,DAUXNEXT,DLOADNEXT,DTAU,RELERR,EPSILON,DTVI:REAL;
      DTVNEXT,COSZENITHANGL,RUNTIME,ROOMAREA,TAI,COSTHETA:REAL;
      DDGI,LOWSET,HISET,TAB,TAD,TAUA,TAUAI,A1,A2,A3,TAUI:REAL;
      RIN,RON,TIME,NEXTTIME,FURNACERATE:REAL;
      R1,R2,R3,R4,R5,R6,R7,R8,R9,R10,R11,R12,R13,R14,R15:REAL;
      R16,R17,R18,R19,R20,R21,R22,R23,R24,R25:REAL;
      C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15,C16:REAL;
      DGAREA,TWAREA,TA,TANEXT,OPENTIME,CLOSETIME:REAL;
      NITEFACTOR,SMNITEFACTOR,TAU,TAVE,TSWING:REAL;
      OURANGL,SSANGL,DCLNATN,HT,HD,KT,LAT,IT,IB,ID,RB,DG,AZMTH,TW:REAL;
      TAUD,RHOR,ALFA,TAUB,TAUBN,RHOG,ALFAB,ALFABN,ALFAD:REAL;
 (*INTEGERS*)
      FLAG1,FLAG2,FLAG3,COUNT1,COUNT2:INTEGER;
      I,J,K,L,M,N,O,P,Q,R,S:INTEGER;
      CN,DAYOFYEAR,MONTH:INTEGER;
(*  *)
(*  *)
PROCEDURE IRRADIATION(TAU:REAL);
(*GIVEN THE LATITUDE, THE DAY OF THE YEAR, THE AVERAGE DAILY RADIATION*)
(* AND THE TIME OF DAY, THIS ROUTINE WILL YIELD THE HOURLY BEAM AND*)
(*DIFFUSE INCIDENT RADIATION ON THE TROMBE WALL AND FOR DIRECT GAIN*)
BEGIN
      OURANGL:=(15.0*TAU-180.0)*0.01745329252;
      DCLNATN:=0.40927970959*SIN((284+DAYOFYEAR)/365.0*6.2831853);
      COSZENITHANGL:=COS(DCLNATN)*COS(LAT)*COS(OURANGL)
      +SIN(DCLNATN)*SIN(LAT);
      IF COSZENITHANGL<=0.0 THEN
      BEGIN
            TW:=0.0;
            DG:=0.0;
      END
      ELSE
      BEGIN
         SSANGL:=-SIN(LAT)/COS(LAT)*SIN(DCLNATN)/COS(DCLNATN);
         SSANGL:=ARCTAN(SQRT(1.0-SQR(SSANGL))/SSANGL);
         HD:=(0.775+0.00653*(SSANGL*57.29578-90.0)-(0.505+0.00455*(SSANGL*
         57.29578-90.0))*COS(2.0071286*KT-1.7078001))*HT;
         ID:=(0.1308996939*(COS(OURANGL)-COS(SSANGL))/(SIN(SSANGL)-SSANGL*
         COS(SSANGL)))*HD;
```

```
(*DIFFUSE HOURLY RADIATION ON A HORIZONTAL PLATE*)
IF ID<0.0 THEN ID:=0.0;
IT:=(0.1328996939*(0.409+0.5016*SIN(SSANGL-1.0471976)+(0.6609-
0.4767*SIN(SSANGL-1.0471976))*COS(DURANGL))*(COS(DURANGL)
-COS(SSANGL))/(SIN(SSANGL)-SSANGL*COS(SSANGL)))*HT;
IF IT<0.0 THEN IT:=0.0;
(*BEAM HOURLY RADIATION ON A HORIZONTAL PLATE*)
IB:=IT-ID;
IF IB<0.0 THEN IB:=0.0;
ALFA:=1.0-TAUD*RHOR*DGAREA/ROOMAREA/(1.0-RHOR*(1.0-DGAREA/ROOMAREA
*TAUD));
RB:=(-SIN(DCLNATN)*COS(LAT)*COS(AZMTH)+COS(DCLNATN)*SIN(LAT)*
COS(AZMTH)*COS(DURANGL)+COS(DCLNATN)*SIN(AZMTH)*SIN(DURANGL))/
COSZENITHANGL;
COSTHETA:=RG*COSZENITHANGL;
(*CALCULATE THE TAUB FOR GLAZING AND ALFAB FOR TROMBE WALL*)
IF COSTHETA>0.0 THEN
BEGIN
  ALFAB:=ALFABN*EXP(0.12*LN(COSTHETA));
  THETA:=ARCTAN(SQRT(1.0-SQR(COSTHETA))/COSTHETA);
  SINTHETAC:=SIN(THETA)/NC;
  THETAC:=ARCTAN(SINTHETAC/SQRT(1.0-SQR(SINTHETAC)));
  RHO1:=SQR(SIN(THETAC-THETA))/SQR(SIN(THETAC+THETA));
  RHO2:=RHO1*SQR(COS(THETAC+THETA))/SQR(COS(THETAC-THETA));
  TAUA:=EXP(-KAPPA*CN*THICKGLAS/COS(THETAC));
  TAUB:=0.5*((1.0-RHO1)/(1.0+(2.0*CN-1.0)*RHO1)
      +(1.0-RHO2)/(1.0+(2.0*CN-1.0)*RHO2))*TAUA;
  TAUA1:=EXP(-KAPPA*THICKGLAS/COS(THETAC));
  TAU1:=TAUB/TAUA*TAUA1;
  TAB:=TAUB*ALFAB/(1.0-(1.0-ALFAB)*(TAUA-TAUB)
     +(1.0-TAUA1)*(A1+(A2+A3)*TAU1));
END
ELSE
BEGIN
  (*WRITELN(' FOR NEXT LINE THETA GREATER THAN 90');*)
   TAB:=0.0;
   TAUB:=0.0;
  IB:=0.0;
  IT:=ID;
END;
(*CALCULATE THE HEAT FLUX DUE TO DIRECT GAIN*)
DG:=DGAREA*ALFA*(TAUB*IB*RB+TAUD*ID/2.0+RHOG*TAUD*IT/2.0);
IF DG<0.0 THEN DG:=0.0;
(*CALULATE THE HEAT FLUX AT THE TROMBE WALL*)
TW:=TWAREA*(IB*RB*TAB+ID*TAD/2.0+RHOG*IT*TAD/2.0);
IF TW<0.0 THEN TW:=0.0;
END;
END;
(*  *)
(*  *)
```

```
[illegible] IN THE WALLS*)
   [illegible](T[[2]-T[[1]]/R3)/C1;
   [illegible](T[[ ]-T[[2]]/R4)/C2;
   [illegible](T[[ ]-T[[3]]/R5)/C3;
   [illegible](T[[ ]-T[[4]]/R6)/C4;
   [illegible](T[[15]-T[[5]]/R7)/C5;
   [illegible](T[[ ]-T[[6]]/R11)/C6;
   [illegible](T[[ ]-T[[7]]/R12)/C7;
   [illegible](T[[ ]-T[[8]]/R13+(T[[16]-T[[8]]/R9)/C8;
   [illegible](T[[10]-T[[9]]/R14)/C9;
   [illegible]/R14+(T[[15]-T[[10]]/R15)/C10;
   [illegible](T[[15]-T[[11]]/R17)/C11;
   [illegible](T[[15]-T[[12]]/R19)/C12;
   [illegible](T[[14]-T[[13]]/R21)/C13;
   [illegible]-T[[14]]/R24+(T[[13]-T[[14]]/R21)/C14;
   [illegible](T[[15]-T[[17]]/R20)/C15;

[illegible]
[illegible] VALUES OF THE TEMPERATURES AT THE NODES*)
[illegible] INTO THE FUTURE*)
   [illegible] 14 DO
   [illegible]*DTAU;
   [illegible]/DTAU+DAUXNEXT/DTAU+TP[5]/R7+(TANEXT/R1+TP[1]/R2+
   [illegible]/(1.0/R1+1.0/R2+1.0/R8+1.0/R9)+TP[14]/R24+TP[10]
   [illegible]/R17+TP[12]/R19+TANEXT*(1.0/R22+1.0/R23))/
   [illegible]+1.0/R24+1.0/R15+1.0/R17+1.0/R19+1.0/R22+
   [illegible]/(1.0/R1+1.0/R2+1.0/R8+1.0/R9));
   [illegible] :=(TANEXT/R1+TP[1]/R2+TP[15]/R8+TP[8]/R9)/(1.0/R1+
   [illegible]+1.0/R8+1.0/R9);
   [illegible] :=T[17]+DT[17]*DTAU;
[illegible].
[illegible]
[illegible] CORRECTTEMP.
[illegible] THE CORRECTED TEMPERATURES AT THE NODES FOR ONE TIME STEP*)
[illegible] THE FUTURE*)
[illegible]
   FOR K:=1 TO 14 DO
   TC[K]:=T[K]+DTAU/2.0*(DTO[K]+DT[K]);
   TC[15]:=(OLOADNEXT/DTAU+DAUXNEXT/DTAU+TC[5]/R7+(TANEXT/R1+TC[1]/R2+
    TC[8]/R9)/R8/(1.0/R1+1.0/R2+1.0/R8+1.0/R9)+TC[14]/R24
    +TC[10]/R15+TC[11]/R17+TC[12]/R19+TANEXT*(1.0/R22+
    1.0/R23))/(1.0/R7+1.0/R8+1.0/R24+1.0/R15+1.0/R17+1.0/R19
    +1.0/R22+1.0/R23-1.0/R8/R8/(1.0/R1+1.0/R2+1.0/R8+1.0/R9));
   TC[16]:=(TANEXT/R1+TC[1]/R2+TC[15]/R8+TC[8]/R9)/(1.0/R1+
```

```
      1.0/R2+1.0/R8+1.0/R9);
     TC[17]:=T[17]+DTAU/2.0*(DTC[17]+DT[17]);
END;
(*  *)
(*  *)
PROCEDURE FINDTEMP;
(*FINDS THE TEMPERATURES AT THE NODES FOR THE NEXT TIME STEP*)
(*IN THE FUTURE*)
BEGIN
(*LOAD THE TEMPERATURES IN TO THE WORKING REGISTERS*)
     FOR I:=1 TO 17 DO
          TI[I]:=T[I];
          DTVI:=DTV/DTAU;
          DDGI:=DDG/DTAU;
          TAI:=TA;
(*FIND THE CURRENT TEMPERATURE GRADIENTS AND PREDICT THE NEXT TEMPS*)
     FINDDERIVATIVE;
     FOR I:=1 TO 14 DO
     DTC[I]:=DT[I];
     DTC[17]:=DT[17];
     PREDICTTEMP;
(*LOAD THE PREDICTED TEMPERATURES INTO THE WORKING SLOTS,*)
(*FIND THE TEMPERATURE GRADIENTS AT THE PREDICTED TEMPS*)
(*AND ITERATE AS NECESSARY TO FIND THE CORRECT NODE TEMPS*)
     COUNT1:=1;
     FLAG1:=0;
     WHILE FLAG1=0 DO
     BEGIN
          FOR I:=1 TO 17 DO
          TI[I]:=TP[I];
          DTVI:=DTVNEXT/DTAU;
          DDGI:=DDGNEXT/DTAU;
          TAI:=TANEXT;
          FINDDERIVATIVE;
          (*CALCULATE THE CORRECTED TEMPERATURES*)
          CORRECTTEMP;
          (*DETERMINE IF THE CORRECTED AND PREDICTED TEMPS ARE CLOSE*)
          FLAG2:=0;
          FOR I:=1 TO 17 DO
          BEGIN
               RELERR:=ABS(2.0*(TC[I]-TP[I])/(TC[I]+TP[I]));
               IF RELERR>EPSILON THEN
               FLAG2:=1;
          END;
          (*IF THE RELATIVE ERROR IS TOO LARGE, SET TP EQUAL TO*)
          (*TC AND DO AGAIN*)
          IF FLAG2=1 THEN
          BEGIN
               FOR I:=1 TO 17 DO
               TP[I]:=TC[I];
```

```
                COUNTI:=COUNTI+1;
            END
            ELSE
            FLAGI:=1;
            IF COUNTI=20 THEN
            BEGIN
                WRITELN(' ERROR:  CONVERGENCE IS NOT ACHIEVED.');
                FLAGI:=1;
            END;
        END;
        (*RETURN THE NEW TEMPERATURES TO THE MAIN PROGRAM*)
        FOR I:=1 TO 17 DO
        T[I]:=TC[I];
END;
(*  *)
(*  *)
PROCEDURE ENTERDATA;
BEGIN
(*READ IN THE PARAMETERS ABOUT THE HOUSE AND LOCATION*)
      READ(RIN,NITEFACTOR);(*SOUTH GLAZING AND NITE INSULATION*)
      READ(R2);(*THROUGH GLASS TO TROMBE WALL FROM SUNSPACE*)
      READ(R3,R4,R5,R6);(*THE INTERNAL RESISTANCE OF TROMBE WALL*)
      READ(R7);(*CONVECTION FROM TROMBE WALL TO INTERIOR*)
      READ(R8);(*FROM SUNSPACE TO INTERIOR THROUGH DG GLAZING*)
      READ(RSN,SNNITEFACTOR);(*MASS TRANSFER AND CONVECTION TO STORAGE MASS*)
      READ(R10);(*INSULATION BETWEEN STORAGE MASS AND OUTSIDE*)
      READ(R11);(*ONE FOURTH THE RESISTANCE OF THE STORAGE MASS*)
      R12:=R11;
      R13:=R11;
      R14:=R11;
      READ(R15);(*CONVECTION FROM STORAGE MASS TO INTERIOR*)
      READ(R16);(*RESISTANCE IN OUTSIDE HALF OF WALLS*)
      READ(R17);(*RESISTANCE IN IN SIDE HALF OF WALLS*)
      READ(R18);(*RESISTANCE IN OUTSIDE HALF OF CEILING*)
      READ(R19);(*RESISTANCE IN IN SIDE HALF OF CEILING*)
      READ(R20);(*RESISTANCE IN  HALF OF FLOOR SLAB*)
      R21:=R20;
      READ(R22);(*RESISTANCE IN NON-SOUTH GLAZING*)
      READ(R23);(*RESISTANCE TO AIR CHANGES*)
      READ(R24);(*CONVECTION FROM FLOOR TO INTERIOR*)
      READ(R25);(*PERIMETER RESISTANCE*)
      READ(C1,C2,C3,C4,C5);(*TROMBE WALL CAPACITANCE*)
      READ(C7);(*ONE FOURTH THE CAPACITANCE OF THE STORAGE MASS*)
      C6:=C7/2.0;
      C8:=C7;
      C9:=C7;
      C10:=C8;
      READ(C11);(*CAPACITANCE OF WALLS*)
      READ(C12);(*CAPACITANCE OF CEILING*)
      READ(C13);(*ONE HALF CAPACITANCE OF FLOOR*)
```

```
    C14:=C13/2.0;
    C15:=C14;
    READ(LAT);(*THE LATITUDE IN DEGREES*)
    LAT:=LAT*0.01745329252;
    READ(AZMTH);(*THE DEVIATION IN DEGREES FROM A SOUTH FACING*)
                (*COLLECTOR WALL. WEST IS POSITIVE.*)
                (*EAST IS NEGATIVE*)
    AZMTH:=AZMTH*0.01745329252;
    READ(CN);(*THE NUMBER OF GLAZINGS ON SUNSPACE*)
    READ(A1,A2,A3);(*TOP LOSS RATIO COEFFICIENTS*)
    READ(THICKGLAS);(*THE THICKNESS OF EACH GLAZING*)
    READ(NC);(*THE INDEX OF REFRACTION OF GLASS*)
    READ(KAPPA);(*THE EXTINCTION COEFFICIENT*)
    THETAC:=ARCTAN(0.8660254/NC/SQRT(1.0-SQR(0.8660254/NC)));
    RHO1:=SQR(SIN(THETAC-1.0471976))/SQR(SIN(THETAC+1.0471976));
    RHO2:=RHO1*SQR(COS(THETAC+1.0471976))/SQR(COS(THETAC-1.0471976));
    TAUA:=EXP(-KAPPA*CN*THICKGLAS/COS(THETAC));
    TAUD:=0.5*((1.0-RHO1)/(1.0+(2.0*CN-1.0)*RHO1)+
              (1.0-RHO2)/(1.0+(2.0*CN-1.0)*RHO2))*TAUA;
    READ(ALFABN);(*TROMBE WALL NORMAL BEAM ABSORBTANCE*)
    ALFAD:=ALFABN*0.9201877;(*TROMBE WALL DIFFUSE ABSORB*)
    TAUA1:=EXP(-KAPPA*THICKGLAS/COS(THETAC));
    TAU1:=TAUD/TAUA*TAUA1;
    TAD:=TAUD*ALFAD/(1.0-(1.0-ALFAD)*(TAUA-TAUD))
      +(1.0-TAUA1)*(A1+(A2+A3)*TAU1);
    READ(RHOR);(*ROOM WALL REFLECTENCE*)
    READ(RHOG);(*GROUND TOTAL REFLECTANCE*)
    READ(DGAREA);(*DIRECT GAIN GLAZING AREA*)
    READ(TWAREA);(*TROMBE WALL AREA EXPOSED TO THE SUN*)
    READ(ROOMAREA);(*INTERIOR ABSORBING AREA*)
    READ(FURNACERATE);(*IN HEAT UNITS PER HOUR*)
    READ(LOWSET,HISET);(*THE THERMOSTAT SETTINGS*)
(*READ IN THE PARTICULARS ABOUT THIS RUN*)
    READ(MONTH);
    READ(RUNTIME);(*THE NUMBER OF HOURS THE SYSTEM IS TO RUN*)
    READ(DTAU);(* THE TIME INCREMENT IN HOURS*)
    READ(EPSILON);(*THE TOLERANCE FOR THE PREDICTOR*)
                  (*CORRECTOR ROUTINE*)
    READ(DAYOFYEAR);(*JULIAN DATE*)
    READ(OPENTIME);(*TIME NITE INSULATION REMOVED*)
    READ(CLOSETIME);(*TIME NITE INSULATION INSTALLED*)
    READ(HT);(*THE MONTHLY AVERAGE TOTAL DAILY RADIATION*)
    READ(KT);(*THE CLEARNESS INDEX*)
    READ(TAVE,TSWING);(*MEAN AMBIENT TEMP AND 1/2 TMAX-TMIN*)
(*INITIAL CONDITIONS. NOTE, ALL RUNS START AT MIDNITE*)
    READ(TA); (*AMBIENT TEMPERATURE AT MIDNITE*)
    READ(QLOADNEXT);(*THE INTERNAL HEAT FROM AUX EQUIPMNT*)
    FOR J:=1 TO 17 DO
    READ(T[J]);(*NODAL TEMPERATURES*)
(*PRINT OUT THE INITIAL CONDITIONS*)
```

```
WRITELN(' SOLAR HOUSE',25);
WRITE(' A COMPUTER SIMULATION OF A RESIDENTIAL ');
WRITELN('STRUCTURE HEATED PASSIVELY BY THE SUN.');
WRITE(' FEATURES OF THIS STRUCTURE INCLUDE HEATING ');
WRITELN('BY DIRECT GAIN, BY TROMBE WALL,');
WRITE(' AND HEAT STORAGE IN AN INSULATED MASS. ');
WRITELN('NIGHT INSULATION CAN ALSO BE INSTALLED.');
{*PRINT THE HEADER*}
  WRITELN;   WRITELN;  WRITELN;
  WRITELN(' THE INPUT DATA');
  WRITELN(' RIN=',RIN,' DAYTIME RESISTANCE IN SOUTH GLAZING');
  WRITELN(' NITEFACTOR=',NITEFACTOR,' NITE INSULATION MULTIPLIER');
  WRITELN(' R2=',R2);
  WRITELN(' R3=',R3);
  WRITELN(' R4=',R4);
  WRITELN(' R5=',R5);
  WRITELN(' R6=',R6);
  WRITELN(' R7=',R7);
  WRITELN(' R8=',R8);
  WRITELN(' RDN=',RDN,' DAYTIME TRANSFER FROM SUNSPACE TO DTM');
  WRITELN(' SNNITEFACTOR=',SNNITEFACTOR,' NITETIME MULTIPLIER');
  WRITELN(' R10=',R10);
  WRITELN(' R11=',R11);
  WRITELN(' R12=',R12);
  WRITELN(' R13=',R13);
  WRITELN(' R14=',R14);
  WRITELN(' R15=',R15);
  WRITELN(' R16=',R16);
  WRITELN(' R17=',R17);
  WRITELN(' R18=',R18);
  WRITELN(' R19=',R19);
  WRITELN(' R20=',R20);
  WRITELN(' R21=',R21);
  WRITELN(' R22=',R22);
  WRITELN(' R23=',R23);
  WRITELN(' R24=',R24);
  WRITELN(' R25=',R25);
  WRITELN(' C1=',C1);
  WRITELN(' C2=',C2);
  WRITELN(' C3=',C3);
  WRITELN(' C4=',C4);
  WRITELN(' C5=',C5);
  WRITELN(' C6=',C6);
  WRITELN(' C7=',C7);
  WRITELN(' C8=',C8);
  WRITELN(' C9=',C9);
  WRITELN(' C10=',C10);
  WRITELN(' C11=',C11);
  WRITELN(' C12=',C12);
  WRITELN(' C13=',C13);
```

```
WRITELN(' C14=',C14);
WRITELN(' C15=',C15);
WRITELN(' LAT=',LAT);
WRITELN(' AZMTH=',AZMTH);
WRITELN(' CN=',CN);
WRITELN(' A1=',A1);
WRITELN(' A2=',A2);
WRITELN(' A3=',A3);
WRITELN(' THICKGLAS=',THICKGLAS);
WRITELN(' NC=',NC);
WRITELN(' KAPPA=',KAPPA);
WRITELN(' TAUD=',TAUD);
WRITELN(' ALFABN=',ALFABN);
WRITELN(' ALFAD=',ALFAD);
WRITELN(' RHOR=',RHOR);
WRITELN(' RHOG=',RHOG);
WRITELN(' MONTH=',MONTH);
WRITELN(' DGAREA=',DGAREA);
WRITELN(' TWAREA=',TWAREA);
WRITELN(' ROOMAREA=',ROOMAREA);
WRITELN(' FURNACERATE=',FURNACERATE);
WRITELN(' LOWSET=',LOWSET);
WRITELN(' HISET=',HISET);
WRITELN(' RUNTIME=',RUNTIME);
WRITELN(' DTAU=',DTAU);
WRITELN(' EPSILON=',EPSILON);
WRITELN(' DAYOFYEAR=',DAYOFYEAR);
WRITELN(' OPENTIME=',OPENTIME);
WRITELN(' CLOSETIME=',CLOSETIME);
WRITELN(' HT=',HT);
WRITELN(' KT=',KT);
WRITELN(' TAVE=',TAVE);
WRITELN(' TSWING=',TSWING);
WRITELN(' TA=',TA,' THE OUTSIDE TEMP AT MIDNITE');
WRITELN(' OLOADNEXT=',OLOADNEXT);
WRITELN;    WRITELN;    WRITELN;
WRITE(' TIME',' AMBIENTTEMP','OTW':8,'ODG':8,'OLOAD':8);
WRITE('OAUX':8,' NODE1 NODE2 NODE3 NODE4 NODE5 NODE6 NODE7 ');
WRITELN('NODE8 NODE9 NODE10 NODE11 NODE12 NODE13');
WRITELN(' NODE14 NODE15 NODE16 NODE17');
WRITELN;
WRITE('0.0':5,TA:12:1,'0.0':8,'0.0':8,OLOADNEXT:8:1,'0.0':8);
FOR J:=1 TO 9 DO
    WRITE(T[J]:6:1);
FOR J:=10 TO 13 DO
    WRITE(T[J]:7:1);
WRITELN;
WRITELN(T[14]:7:1,T[15]:7:1,T[16]:7:1,T[17]:7:1);
END;
(* *)
```

```
(*  *)
BEGIN (*MAIN PROGRAM*)
ENTERDATA;     (*READ IN THE DATA AND THE INITIAL CONDITIONS*)
TIME:=0.0;
NEXTTIME:=DTAU;
DAUXNEXT:=0.0;
FLAG3:=1;
FOR S:=1 TO ROUND(RUNTIME/DTAU) DO
BEGIN
    (* READ IN OR CALCULATE THE NEXT LOADS*)
    (*READ(OLOADNEXT);*)
    TANEXT:=TAVE-TSWING*COS((NEXTTIME-2.0)*0.2617994);
    IF T[15]<LOWSET THEN
        DAUXNEXT:=FURNACERATE*DTAU;
    IF T[15]>HISET THEN
        DAUXNEXT:=0.0;
    IF NEXTTIME<OPENTIME THEN
    BEGIN
        DTW:=0.0;
        DDG:=0.0;
        DTWNEXT:=0.0;
        DDGNEXT:=0.0;
        RI:=RIN*NITEFACTOR;
        RO:=RON*SMNITEFACTOR;
    END
    ELSE IF NEXTTIME>= CLOSETIME THEN
    BEGIN
        DTW:=0.0;
        DDG:=0.0;
        DTWNEXT:=0.0;
        DDGNEXT:=0.0;
        RI:=RIN*NITEFACTOR;
        RO:=RON*SMNITEFACTOR;
    END
    ELSE
    BEGIN
        IRRADIATION(TIME);
        DTW:=TW*DTAU;
        DDG:=DG*DTAU;
        IRRADIATION(NEXTTIME);
        DTWNEXT:=TW*DTAU;
        DDGNEXT:=DG*DTAU;
        RI:=RIN;
        RO:=RON;
    END;
    (*FIND THE NODAL TEMPS FOR THE NEXT TIME INCREMENT*)
    FINDTEMP;
    IF FLAG3>10 THEN
      BEGIN
    WRITE(NEXTTIME:8:0,TANEXT:12:1,DTWNEXT:8:0,DDGNEXT:8:0,OLOADNEXT:8:0,
```

```
         DAUXNEXT,8:8);
  FOR J:=1 TO 9 DO
        WRITE(T[J],6:1);
  FOR J:=10 TO 13 DO
        WRITE(T[J],7:1);
  WRITELN;
  WRITELN('  ',T[14],7:1,T[15],7:1,T[16],7:1,T[17],7:1);
 END;
  TIME:=TIME+DTAU;
  NEXTTIME:=NEXTTIME+DTAU;
  TA:=TANEXT;
  IF TIME>=24.0 THEN
  BEGIN
  TIME:=TIME-24.0;
  FLAGS:=FLAGS+1;
  END;
  IF NEXTTIME>=24.0 THEN NEXTTIME:=NEXTTIME-24.0;
END;
END.
```

Explanation of Variables

Variables used Primarily by the Main Program.

T(1) through T(17): the temperatures at nodes 1 through 17 at the current time.

RUNTIME: the number of hours that the program is to simulate. The minimum value of this input variable is 264.0, for the program runs internally for 240.0 simulated hours to reach cyclic steady state.

FURNACERATE: the heat output per hour of thé furnace.

LOWSET: the temperature below which the furnace kicks on.

HISET: the temperature above which the furnace turns off.

TAVE: the monthly-average temperature.

TSWING: half the difference between the monthly-average high and the monthly-average low temperature.

TIME: the current time.

NEXTTIME: the time at one time step into the future.

OPENTIME: the time of day that night insulation is to be removed.

CLOSETIME: the time of day that night insulation is to be installed.

MONTH: an integer flag to identify the month of the year. This input variable will be assigned a value from 1 to 12.

R1N: the value of resistor R1 when night insulation is not installed.

NITEFACTOR: the value by which R1N is multiplied when night insulation is in place.

R9N: the value of resistor R9 during the day.

SMNITEFACTOR: the value by which R9 is multiplied when the system is operating in night configuration.

Variables used Primarily by the Differential Equation Solver.

TP(1) to TP(17): the predicted temperatures at the nodes.

TC(1) to TC(17): the corrected temperatures at the nodes.

TI(1) to TI(17): a dummy variable used to hold calculated nodal temperatures.

DT(1) to DT(17): the temperature gradients at the nodes.

DTO(1) to DTO(17): a dummy variable used to hold calculated values of temperature gradients.

TAU: the time of day.

DTAU: the time step size in hours. In R-C circuit analysis, the time step size is determined from the relation:

$$DTAU \leq \text{Minimum } (Cx/\sum(1/Ry))$$

where Cx is the value of each capacitor and Ry is the value of each resistor directly connected to capacitor Cx.

RELERR: the relative error between the pr.dicted and the corrected temperature at each node.

EPSILON: the maximum allowable relative error. A value of 0.001 is recommended.

TA: the ambient temperature at the current time of day.

TANEXT: the ambient temperature at one time step in the furure.

TAI: a working variable for ambient temperature.

QAUXNEXT: the furnace input for node 15 at one time step in the future.

QLOADNEXT: the internally generated heat input for node 15 at one time step in the future.

R1 to R25: the values of resistors R1 to R25.

C1 to C15: the values of capacitors C1 to C15.

Variables used in the Calculation of Solar Gain.

CN: the total number of glazings on the collector.

NC: the index of refraction of glass.

KAPPA: the extinction coefficient of glass.

THICKGLAS: the thickness of one of the glazings on the collector.

A1, A2, and A3: collector loss ratio coefficients.

ALFA: the effective absorptance of the interior surfaces.

ALFAB: the beam absorptance of the surface of the Trombe wall.

ALFABN: the normal beam absorptance of the surface of the Trombe wall.

ALFAD: the diffuse absorptance of the surface of the Trombe wall.

RHOG: the reflectance of the ground surrounding the collector.

RHOR: the effective reflectance of the interior surfaces.

RHO1, RHO2: the reflectance of the collector glazings.

TAUBN: the normal beam transmittance of the collector glazings.

TAUB: the beam transmittance of the collector glazings.

TAUD: the diffuse transmittance of the collector glazings.

TAB: the effective transmittance-absorptance product for beam radiation incident on the Trombe wall.

TAD: the effective transmittance-absorptance product for diffuse radiation incident on the Trombe wall.

TAUA: the transmittance due to absorptance of all of the collector glazings.

TAUA1: the transmittance due to absorptance of one of the collector glazings.

TAU1: the total transmittance of one of the collector glazings.

DGAREA: the area of the collector dedicated to direct gain.

TWAREA: the area of the collector dedicated to indirect gain.

ROOMAREA: the surface area of the interior, less glazed area.

QTW: the indirect gain heat input at node 1 at the current time.

QTWNEXT: the indirect gain heat input at node 1 at one time step in the future.

QTWI, TW: working variables for indirect gain heat inputs.

QDG: the direct gain heat input at node 14 at the current time.

QDGNEXT: the direct gain heat input at node 14 at one time step in the future.

QDGI, DG: working variables for direct gain heat inputs.

OURANGL: the hour angle.

SSOURANGL: the sunset hour angle.

THETA: the angle of incidence of beam radiation.

SINTHETA: sin(THETA).

COSTHETA: cos(THETA).

THETAC: the angle of beam radiation within the glazing after refraction at the air-glass interface.

SINTHETAC: sin(THETAC).

COZENITHANGL: the cosine of the angle of incidence of beam radiation on a horizontal surface.

DAYOFYEAR: Julian date.

AZMTH: azimuth in degrees.

LAT: latitude in degrees.

DECLNATN: declination.

RB: the ratio of beam radiation on a tilted surface to beam radiation on a horizontal surface.

HT: the daily total radiation on a horizontal surface.

HD: the daily diffuse radiation on a horizontal surface.

KT: the clearness index.

IT: the hourly total radiation.

ID: the hourly diffuse radiation.

IB: the hourly beam radiation.

Required Input Information

Values for the following variables are required for the input data file. Information must be in the order listed below, but may be grouped in any way. Asterisked values are integers. All others are real numbers.

Parameters of the Structure and Location.

R1N, NITEFACTOR, R2, R3, R4, R5,

R6, R7, R8, R9N, SMNITEFACTOR, R10,

R11, R15, R16, R17, R18, R19,

R20, R22, R23, R24, R25,

C1, C2, C3, C4, C5, C7, C11, C12, C13,

LAT, AZMTH, CN*, A1, A2, A3,

THICKGLAS, NC, KAPPA, ALFABN, RHOR, RHOG,

DGAREA, TWAREA, ROOMAREA, FURNACERATE, LOWSET, HISET,

Particulars about the Current Run.

MONTH*, RUNTIME, DTAU, EPSILON, DAYOFYEAR*,

OPENTIME, CLOSETIME, HT, KT, TAVE, TSWING,

Initial Conditions.

TA, QLOADNEXT, T(1), T(2), T(3), T(4),

T(5), T(6), T(7), T(8), T(9), T(10), T(11),

T(12), T(13), T(14), T(15), T(16, T(17).

If the program is modified to utilize internally generated heat Q_L, the hourly heat input rate must be included in the input file for each time step in the simulation:

QLOADNEXT, QLOADNEXT, ...

AD-A124 900 THE SIMULATION OF A PASSIVE SOLAR ENERGY SYSTEM(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGINEERING M P SLATE DEC 82 AFIT/GA/AA/82D-8

2/2

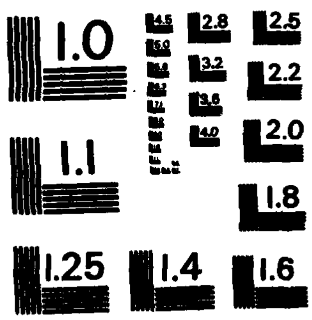
UNCLASSIFIED

F/G 11/4 NL

END

DATE

FILMED



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Appendix B

Details of the construction of test cell #1 in Los Alamos, New Mexico, along with calculated input information for the modified computer program is presented in this appendix. Figure 4 and Appendix A will be useful in following the development here. Unless otherwise indicated, material properties are from Mazria or the Carrier System Design Manual (Ref 10).

The test cell measured 86 in. (north-south) by 62 in. (east-west) by 120 in. The west wall of the cell was a common wall between cell #1 and cell #2. Because the wall was well insulated and because temperatures on both sides of the wall were maintained at or near 65 F, it was assumed that no heat transfer took place across the wall.

The test cell did not have direct gain heating, nor a masonry floor, a detached storage mass, or a sunspace. For this reason, nodes 6, 7, 8, 9, 10, 13, 14, 16, and 17 were eliminated from the circuit. This was done by setting the values of resistors R8, R9, R10, R11, R12, R13, R14, R15, R20, R21, R24, and R25 to $1X10^{15}$ hr-F/B, resistor R1 to $1X10^{-15}$ hr-F/B, and capacitors C6, C7, C8, C9, C10, C13, C14, and C15 to 0.01 B/F. In addition, the test cell had windows and no significant thermal mass in the conventional walls. For this reason, resistor R22 was used to model resistance to heat flow in the walls, and node 11, with associated resistors R16 and R17 and capacitor C11 was used for the floor of the cell.

Resistor R2. The U-value for the double glazings and air space in front of the Trombe wall was given in McFarland as 0.46 B/ft^2-hr-F. The glazed area is 23.4 ft^2.

R2 = 1 /(0.46 X 23.4)

= 0.0929023 hr-F/B

Resistors R3 through R6. From McFarland, the conductivity of the concrete in the Trombe wall was 1.0 B/ft-hr-F. For a wall with a cross sectional area of 29.8 ft^2 and a thickness of 15-5/8 in., one fourth the total internal resistance is:

R3 = 1 X (15-5/8)/(12 X 4 X 29.8)

= 0.0109235 hr-F/B

R3 = R4 = R5 = R6

Resistor R7. The natural convection air film coefficient for a vertical wall is 0.68 ft^2-hr-F/B. The exposed area of the Trombe wall is 29.8 ft^2.

R7 = 0.68/29.8

= 0.0224161 hr-F/B

Resistors R16 and R17. The bottom of the test cell sat on 2X4 framing and was exposed to outside air flow. Construction, from outside to inside with associated resistances in ft^2-hr-F/B was:

Outside Air Film	0.25
5/8 in. Plywood	0.78125
2X6 Frame and R22 Insulation	22.0
5/8 in. Plywood	0.78125
Total Resistance	23.8125

Floor area: 37.03 ft^2

R16 = 23.8125/37.03

= 0.6430983 hr-F/B

For resistor R17:

Inside Air Film	0.92

R17 = 0.92/37.03

= 0.0248462

Resistors R18 and R19. Construction of the ceiling and roof, from outside to inside with associated resistances in ft^2-hr-F/B was:

Outside Air Film	0.17
Rolled Roofing	0.15
90# Felt	0.06
5/8 in. Plywood	0.78125
Air Space	0.85
2X6 Frame and R22 Insulation	22.0
Galvanized Sheet Metal	0.0
Total Resistance	24.01125

Ceiling Area: 37.03 ft^2

R18 = 24.01125/37.03

= 0.6484659 hr-F/B

For resistor R19:

Inside Air Film	0.61

R19 = 0.61/37.03

= 0.0164741 hr-F/B

Resistor R22. Three different constructions with associated resistances RA, RB, and RC were modeled with resistor R22. Construction, from outside to inside with associated resistances in ft^2-hr-F/B follow. For the north and east wall:

Outside Air Film	0.17
5/8 in. Plywood	0.78125
2X4 Frame and R11 Insulation	11.0
1 in. Polystyrene	5.0
Inside Air Film	0.68
Total Resistance	17.63125

Area: 105.3 ft^2

RA = 17.63125/105.3 = 0.1673853

For the access door:

Outside Air Film	0.17
5/8 in. Plywood	0.78125
4 in. Polystyrene	20.0
Inside Air Film	0.68
Total Resistance	21.63125

RB = 21.63125/ 18.0 = 1.2017361

For the south wall:

Outside Air Film	0.17
5/8 in. Plywood	0.78125

4-1/3 in. Polystyrene	22.5
Inside Air Film	0.68
Total Resistance	24.13125

Area: 21.87 ft^2

RC = 24.13125/21.87 = 1.1035633

Resistor R22 was the equivalent of these three parallel resistors.

R22 = 1/(1/RA + 1/RB + 1/RC)

= 0.1296592 hr-F/B

Resistor R23. The infiltration rate was 3 air changes per hour. Applying Eq 13:

ρc_p 0.013 B/ft^3-F

V 370.28 ft^3

n 3 1/hr

Q = 0.013 X 370.28 X 3 = 14.4408 B/hr-F

R23 = 1/14.4408

= 0.0692481 hr-F/B

Capacitors C1 through C5. From McFarland, the total capacitance of the Trombe wall was 952 B/F.

C1 = 952.0/8 = 119.0 B/F

C2 = 952.0/4 = 238.0 B/F

C3 = C4 = C2

C5 = C1

Capacitor C11. Only mass inside the insulation was effective as thermal mass. As an estimation, all of the plywood floor and half of the 2X6 frame running east-west on 16 in. centers was included.

Volume of Plywood	1.93 ft^3
Density	34.0 lbm/ft^3
Specific Heat	0.29 B/lbm-F
Heat Capacity of Plywood	19.02 B/F
Volume of half of Frame	0.97 ft^3
Density	27.0 lbm/ft^3
Specific Heat	0.57 B/lbm-F
Heat Capacity of Joists	14.93 B/F

The value of capacitor C11 will be the sum of the above components.

$$C11 = 14.93 + 19.02$$
$$= 33.95 \text{ B/F}$$

Capacitor C12. Significant mass in the ceiling comes from the sheet metal and half of the 2X6 joists.

Volume of Metal	0.0964 ft^3
Density	489.0 lbm/ft^3
Specific Heat	0.12 B/lbm-F
Heat Capacity of Metal	5.66 B/F
Heat Capacity of Joists	14.93 B/F

$$C12 = 5.66 + 14.93$$
$$= 20.59 \text{ B/F}$$

LAT. 35.8 degrees.

AZMTH. 0.0 degrees.

CN. 2 glazings.

A1. 0.15.

A2. 0.62.

A3. 0.0

THICKGLAS. 0.1875 in.

NC. 1.526.

KAPPA. 0.5452 in.

ALFABN. 0.95.

RHOR. This variablewas not used because the cell did not have direct gain heating. The value was set at 0.5.

RHOG. 0.3 estimated.

DGAREA. 0.0 ft^2.

TWAREA. 23.4 ft^2.

ROOMAREA. This variable was not used because the test cell did not utilize direct gain. The value was set at 100 ft^2.

FURNACERATE. 900 B/hr.

LOWSET. 65 F.

HISET. 66 F.

DTAU. In R-C circuit analysis, the time step size is determined from the relation:

$$DTAU \leq \text{Minimum}(Cx/\sum(1/Ry))$$

where Cx is the value of each capacitor and Ry is the value of each resistor directly connected to capacitor Cx. At node 12, resistors R18 and R19 are attached to capacitor C12.

$$C12/(1/R18 + 1/R19) = 20.59/(1/0.648 + 1/0.0165)$$
$$= 0.33 \text{ hr}$$

This relation was computed for all capacitors. Node 12 yielded the smallest time. As DTAU must be smaller than this minimum,

DTAU = 0.25 hr

EPSILON. 0.001.

DAYOFYEAR. 348.

OPENTIME and CLOSETIME. As no night insulation was specified, these variables were assigned values so that they did not interfere with the program.

OPENTIME = -5.0

CLOSETIME = 30.0

KT. 0.75 estimated.

TA. 28 F.

T(1). 67.0 F.

T(2). 69.0 F.

T(3). 71.0 F.

T(4). 70.5 F.

T(5). 70.0 F.

T(6) to R(10) and T(13), T(14) and T(17). These correspond to isolated nodes and were set at 99.0 F.

T(11). 68.0 F.

T(12). 68.0 F.

T(15). 68.0 F.

T(16). 28.0 F.

TA, IT, and ITV. The modified computer program read in, at each time step, the ambient temperature, and the hourly rates of solar insolation on a horizontal and on a vertical surface in B/ft^2-hr. These data were recorded at Los Alamos for the entire 1980-81 winter. On 14 December, the values recorded were:

Time	TA	IT	ITV
01	27	0	0
02	26	0	0
03	25	0	0
04	26	0	0
05	27	0	0
06	26	0	0
07	27	0	0
08	27	4	3
09	27	34	24
10	32	130	213
11	39	148	276
12	42	167	296
13	43	167	295
14	45	147	273
15	46	109	232
16	46	59	173
17	42	7	46
18	37	0	0
19	34	0	0
20	33	0	0
21	33	0	0
22	33	0	0
23	31	0	0
24	30	0	0

Matching the Building Load Coefficients. According to McFarland, the Building Load Coefficient (BLC) of the test

cell was 26.0 B/hr-F with an infiltration rate of 3/hr, and a BLC of 16.0 B/hr-F with an infiltration rate of 1/hr. Calculating the BLC using the values of resistors estimated above, values of 25.15 and 15.53 B/hr-F were obtained. By changing the value of resistor R22 from 0.1296592 to 0.1250163 hr-F/B and the value of resistor R23 from 0.0692481 to 0.0666667 hr-F/B, the design BLC's were closely matched.

Appendix C

Details of the construction of the conventional design for Columbus, Ohio, along with calculated input information for the computer program is presented in this appendix. Figure 4 and Appendix A will be useful in following this development.

The conventional design does not have a sunspace, a Trombe wall, or a detached storage mass. For this reason, nodes 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 are eliminated from the circuit. This is done by setting the values of resistors R2, R3, R4, R5, R6, R7, R9, R10, R11, R12, R13, R14, and R15 to $1X10^{15}$ hr-F/B, the value of resistor R1 to $1X10^{-15}$ hr-F/B, and the values of capacitors C1, C2, C3, C4, C5, C6, C8, C9, and C10 to 0.01 B/F. The values of remaining input information is calculated from Mazria or the Carrier System Design Manual, as applicable, unless otherwise specified.

Resistor R8. Windows are double glazed with a 1/2 in. air gap between glazings. With 150 ft^2 total window area distributed evenly about the structure, 46.875 ft^2 will be built into the south wall.

Transmission Coefficient 0.55 B/ft^2-hr-F

R8 = 1/(0.55 X 46.875)

= 0.0387879 hr-F/B

Resistors R16 and R17. The walls are constructed from outside to in of wood shingles on top of 5/16 in. plywood sheathing, 2X6 frame on 24 in. centers with R19 insulation, and 3/4 in. wood panel on the interior. The wall area is the product of the wall height and the length of the perimeter, less the window area or 1130 ft^2. For resistor R16:

Wall Resistance	23.0
Less the Inside Air Film	0.68
Total Resistance	22.32 ft^2-hr-F/B

R16 = 22.32/1130.0

= 0.0197522 hr-F/B

For resistor R17:

The Inside Air Film	0.68 ft^2-hr-F/B

R17 = 0.68/1130.0

= 0.0006018 hr-F/B

Resistors R18 and R19. The ceiling and roof are constructed, from outside to in, of wood shingles on top of building paper and 5/16 in. plywood sheathing, 2X6 frame on 24 in. centers with R34 insulation, a 25/32 in. wood sub-floor to which is glued 3/4 in. thick acoustical tile. For resistor R18:

Ceiling Resistance	40.285
Less the Inside Air Film	0.61
Total Resistance	39.675 ft^2-hr-F/B

Floor Area: 1500 ft^2

R18 = 39.675/1500.0

= 0.0264501 hr-F/B

For resistor R19:

Inside Air Film $\quad$ 0.61 ft^2-hr-F/B

R19 = 0.61/1500.0

= 0.00040667 hr-F/B

<u>Resistors R20, R21, R24, and R25</u>. The floor is a 6 in. thick concrete slab overlaid with linoleum. R10 insulation extends 2 ft below ground around the 160 ft perimeter. For resistors R20 and R21:

Resistance of 3 in. thick concrete 0.24 ft^2-hr-F/B

Floor Area: 1500 ft^2

R20 = 0.24/1500.0

= 0.00016 hr-F/B

R21 = R20

For resistor R24:

Inside Air Film $\quad$ 0.61 ft^2-hr-F/B

R24 = 0.61/1500.0

= 0.00040667 hr-F/B

For resistor R25, apply Eq 12:

Edge Loss Factor $\quad$ 0.17 B/ft-hr-F

Perimeter $\quad$ 160.0 ft

R25 = 1/(0.17 X 160.0)

= 0.0367647 hr-F/B

<u>Resistor R23</u>. The infiltration rate in the structure is estimated at 3/4 change per hr.

Heat Capacity of Air $\quad$ 0.018 B/ft^3-hr

Volume of Interior $\quad$ 12000.0 ft^3

Air Changes $\quad$ 0.75 1/hr

$$R23 = 1/(0.018 \times 12000.0 \times 0.75)$$
$$= 0.0617284 \text{ hr-F/B}$$

Capacitor C11. Only mass inside the insulation is effective as thermal mass. As an estimate, all of the paneling and half of the 2X6 frame is included.

Volume of Paneling	50.3125 ft^3	
Density	34.0 lbm/ft^3	
Specific Heat	0.29 B/lbm-F	
Heat Capacity of Paneling		496.08 B/F
Volume of Framing	18.3 ft^3	
Density	50.0 lbm/ft^3	
Specific Heat	0.31 B/lbm-F	
Heat Capacity of Framing		283.64 B/F

$$C11 = 496.08 + 283.64$$
$$= 780.24 \text{ B/F}$$

Capacitor C12. All of the sub-floor and acoustical tile, and half of the frame in the roof will be included as thermal mass.

Volume of Tile	93.75 ft^3	
Density	18.0 lbm/ft^3	
Specific Heat	0.19 B/lbm-F	
Heat Capacity of the Tile		320.62 B/F
Volume of Sub-Floor	97.66 ft^3	
Density	50.0 lbm/ft^3	
Specific Heat	0.31 B/lbm-F	
Heat Capacity of the Sub-floor		1513.73 B/F

Volume of Frame	41.67 ft^3	
Density	50.0 lbm/ft^3	
Specific Heat	0.31 B/lbm-F	
Heat Capacity of Framing		645.88 B/F

C12 = 320.62 + 1513.73 + 645.88

= 2480.23 B/F

Capacitors C13, C14, and C15.

Volume of Concrete	750.0 ft^3
Density	140.0 lbm/ft^3
Specific Heat	0.22 B/lbm-F
Total Heat Capacity	23100.0 B/F

C13 = 11550.0 B/F

C14 = 5775.0 B/F

C15 = 5775.0 B/F

LAT. 40.0 degrees.

AZMTH. 0.0 degrees.

CN. 2 glazings.

A1. 0.14.

A2. 0.45.

A3. 0.75.

THICKGLAS. 0.125 in.

NC. 1.526.

KAPPA. 0.5452.

ALFABN. 0.94.

RHOR. 0.4.

RHOG. The ground reflectance depends upon average snow cover for the month. RHOG was estimated at 0.45 for January,

February, and December, 0.25 for March and November, and 0.2 for the remaining months.

DGAREA. 46.875 ft^2.

TWAREA. 0.0 ft^2.

ROOMAREA. 4130 ft^2.

FURNACERATE. 20000.0 B/hr.

LOWSET. 65.0 F.

HISET. 69.0 F.

MONTH. For January, 1. For December, 12.

RUNTIME. To eliminate errors caused by poor selection of initial conditions, 240 hours are simulated internally before printout begins.

RUNTIME = 336.0 hr.

DTAU. The calculations described in Appendix B are carried out for each capacitor in this circuit. The minimum value obtained is 0.63 hr.

DTAU = 0.25 hr.

EPSILON. 0.001.

DAYOFYEAR. Typical days of each month, with their Julian dates, are: 17 January (17), 16 February (47), 16 March (75), 15 April (105), 15 May (135), 11 June (162), 17 July (198), 16 August (228), 15 September (258), 15 October (288), 14 November (318), and 10 December (344).

OPENTIME. -5.0.

CLOSETIME. 30.0

HT, KT, TAVE, TSWING, and TA. For Columbus, Ohio insolation and temperature data are extracted from Liu

and Jordan, and from Cinquemani (Ref 11). Values for TA are calculated using Eq 17. Values for HT are in B/ft^2-day. Values for temperatures are in degrees F.

Month	HT	KT	TSAVE	TSWING	TA
Jan	459.4	0.356	28.4	8.0	21.5
Feb	676.8	0.401	30.3	8.9	22.6
Mar	979.6	0.447	39.2	10.1	30.5
Apr	1352.9	0.470	51.2	11.7	41.4
May	1646.9	0.515	61.1	11.8	50.9
Jun	1812.7	0.561	70.4	11.5	60.4
Jul	1754.9	0.555	73.6	11.2	63.9
Aug	1640.6	0.475	71.9	11.8	61.7
Sep	1281.6	0.433	65.2	12.5	54.7
Oct	945.1	0.441	54.2	12.2	43.6
Nov	537.8	0.302	41.7	9.3	33.6
Dec	387.2	0.351	30.7	10.6	21.5

QLOADNEXT: 0.0.

T(1) to T(17). The initial temperatures of the nodes are set at 60.0 F.

Vita

Mitchell Perry Slate was born 22 March 1954 in Borger, Texas. He attended Homewood-Flossmoor High School in Flossmoor, Illinois, graduating in June, 1971. He then attended the University of Illinois, Urbana Campus, and graduated in January, 1976 with a degree of Bachelor of Science in Mechanical Engineering. Upon graduation, he accepted a commission as an officer in the USAF through the AFROTC program. After training as an ICBM Launch Officer at Vandenberg AFB, California, he served at Ellsworth AFB, South Dakota, as a Minuteman II Missile Combat Crew Member, a Combat Crew Instructor, and a Combat Crew Evaluator. He enrolled at the Air Force Institute of Technology, School of Engineering in June, 1981.

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